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ENERGY EFFICIENCY ANALYSIS OF MULTI-PRESSURE HYDRAULIC SYS- TEM

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ABSTRACT

Husnain Ahmed: Energy Efficiency Analysis of Multi-Pressure Hydraulic System
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High fuel consumption, particle emissions and low energy efficiency are one of the key issues associated with the excavators. In construction machinery excavators are considered main contributors for CO₂ emission, which ultimately have adverse environmental impacts. In this research work, prime mover (electric motor) downsizing is achieved through multi-pressure system. It can be derived that also diesel engine downsizing is possible, which will ultimately contribute to meet these environmental challenges.

Multi-pressure system is a new approach towards the hydraulic hybridization of off-road machines. It is an ultimate replacement of conventional load sensing system. Load sensing is commonly used in off-road machinery as hydraulic power transmission system. Research reveals that huge power losses occur in load sensing system when multiple actuators are working together in a machine because each actuator has different power requirements. In load sensing system actuator is directly coupled with prime mover hence it is dimensioned according to peak power requirements due to which it is bigger in size.

The exclusive feature of multi-pressure system is that it has locally integrated pressure source to the actuator. The system has six power sources for a single actuator. These six power sources are one pump, one accumulator and four pressure transformers. These power sources are connected through on/off valves with actuator.

One cycle of swing operation is performed in this research work. Input electrical energy consumption, mechanical energy consumption of motor and hydraulic energy consumption of pump is determined. Later, the evaluated afore-mentioned energy consumption comparison is made with energy consumption of load sensing system for the same operation. It has been revealed from analysis that multi-pressure system is remarkably energy efficient compared to Load Sensing System. However, experimental results show that there are some controllability issues at lower velocities. The controller needs to be improved when the actuator has low velocity.

Keywords: Modified Load Sensing System, Multi-Pressure Hydraulic System, Hydraulic Power Transmission, Energy Consumption

The originality of this thesis has been checked using the Turnitin OriginalityCheck service.

PREFACE

I would like to start with the name of God Almighty, the most Gracious and the most Merciful. The completion of this thesis is one of the requirements for the completion of Master's degree program in Automation Engineering at Tampere University. This research was conducted at Aalto University's Fluid Power Laboratory under the guidance of Professor Matti Pietola and it was supported by Business Finland (HHYBRID Project) and Academy of Finland (DHHA Project).

I would like to express my gratitude to Professor Matti Pietola who provided me the opportunity to complete this challenging task. I am much obliged to D.Sc. (Tech.) Jyrki Kajaste, who have been instructor of this thesis work; he is indeed one of the most helpful instructors I had ever worked with. I am grateful to you and thank you so much for your trust in my abilities and skills. Valuable inputs provided by Adjunct Professor Matti Linjama, who is supervisor of this thesis made my way easy to complete this challenging task. I would like to say thanks to B.Sc. (Tech.) Otto Gottberg who provided immense help and guidance during the installation and testing of multi-pressure system on excavator. I would like to pay my tribute to B.Sc. (Tech.) Duc Pham, M.Sc. (Tech.) Antti Sinkkonen and Lic.Sc. (Tech.) Heikki Kauranne for their assistance at various stages.

I am greatly thankful to my friend Peer Hamood who made my stay in Espoo a memorable one. I am also thankful to my friends Shoaib Qureshi and Saad Warriach for their continuous support and motivation. I would like to express my gratitude to Umair Ahmed, for helping me in every matter right from the beginning of my Master's studies.

Thank you, Sadia, for your love and support. I would like to share this milestone with you. You are the best life partner and the best thing happened to me. Thank you so much for the sacrifices which you made during my stay in abroad.

I don't know how I should say thanks to my father Dr. M.Younis. I will always remember your financial and moral support during my studies in Finland. You are the reason behind every success in my life. I hope that you are proud of me. I am indebted to my mother who always prayed for me, indeed the completion of this Master's degree was not possible without her prayers.

Tampere, 07 February 2019

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LIST OF ABBREVIATIONS

Direct Driven Hydraulics	DDH
Digital Independent Metering Valve	D-IMV
Fixed Displacement Pump System	FDPS
Flow Pressure Compensator	FPC
High Pressure Compensator	HPC
Load Sensing System	LS
Multi-Pressure Hydraulic System	MPS
Modified Load Sensing System	MLS
Pressure Adjustment Spool	PAS
Pressure Relief Valve	PRV
Pump Side Module	PVP
System Inherent Pressure Losses	SIPL
Tank/Accumulator Logic Valve	T/A-LV

1 INTRODUCTION

Hydraulic power transmission is commonly used in off-road machines to lift heavy loads and to perform high power demanding tasks. Modern control technology has improved the precision and accuracy of hydraulic actuators. Hydraulic systems are well known because of low weight to power ratio, constant supply of high force regardless of speed changes and ability to produce high torque at low speed. These features make it an ideal choice for off-road machines to perform heavy duty tasks. Nowadays research is being done to improve the energy efficiency of hydraulic transmission.

Excavators are back bone of construction industry. Fluid power technology is used in excavators for power distribution. Fluid power technology uses pressurized fluid to generate, control and transmit force and movement of mechanical actuators. Hydraulic systems are used to transmit power from source to the actuator. The basic components of this system are diesel engine, pump, valves and cylinders. The hydraulic systems are considered less energy efficient when compared with electrical and mechanical systems the most prominent cause for that is throttling losses. The recent trend of research is to improve hydraulic system's energy efficiency along with reduction of fuel consumption and particle emission. To reduce the throttling losses research is being done either to replace the conventional proportional valves with number of small size on/off of valves or to design a system without the valves. To reduce the fuel consumption studies are done to implement the smaller size diesel engine by installing local energy recovery units and power sources within the system.

Recent trend of researchers is steered towards the implementation of hybrid solution in mobile machinery. A hybrid system consists of two or more distinct power sources. The advantages of a hybrid solution are twofold, less fuel consumption and improved energy efficiency [1]. Two types of hybrid technologies, hydraulic hybrid and electric hybrid are widely researched on vehicles. These technologies have potential to improve fuel economy through energy recovery and optimization of diesel engine [2]. Hydraulic hybridization is preferred in heavy machineries because hydraulic components are capable to handle high power.

In this thesis an advanced approach toward the hybridization named as multi-pressure hydraulic system (MPS) is implemented on a mini excavator to perform swing operation of boom. This technique is combination of hybridization and digitalization of a hydraulic

system. It has 6 power sources to supply power to the actuator. It has twenty-four on/off valves to direct the flow to or from the actuator to high pressure accumulator or to low pressure accumulator. This system is developed at Tampere University of Technology (TUT). It is a modern concept and a promising technique towards the hydraulic hybridization of off-road machinery. Studies have shown that it not only reduces the power losses of hydraulic systems but also reduces the fuel consumption. This technique is replacement of traditional load sensing technique. Load sensing technique is most frequently used in off-road machines, studies have found that this technique causes more power losses in hydraulic components compared to multi-pressure system as well as fuel consumption is also very high [3] [4].

1.1 Objectives

Following are the objectives of thesis;

- Installation of multi-pressure system on mini excavator to perform swing operation
- Testing the behavior of the system under high and low inertia
- Power and energy consumption calculation of multi-pressure system
- Comparison of power and energy consumption of multi-pressure system with the modified load sensing system

1.2 Scope

The scope of this research work is to implement a hydraulic hybrid system on a micro excavator to perform swing operation. According to literature review, this hybridization approach has not been tested in an environment where inertia is variable. The application of this research work provides an opportunity to extend the scope of multi-pressure system. In context to extent of this master's degree thesis, the system is tested, and analysis are performed to study the power and energy consumption.

1.3 Thesis Outline

The thesis consists of five chapters. The summary of the chapters is described below,

Chapter 2 presents the literature review. Preliminary focus of literature review is to illustrate the key reasons due to which hydraulic systems are considered less efficient. Purpose of the literature review is to present the techniques which have been used so far to reduce the energy consumption in hydraulic systems. In addition, the effectiveness of

multi-pressure is showcased in this chapter. Furthermore, a short but brief overview of promising techniques which have been developed to reduce the power consumption in hydraulic systems is also presented.

Chapter 3 presents the implementation of multi-pressure system on micro-excavator. This chapter summarizes the hydraulic assembly and sensors which are installed in the system. Furthermore, it gives an insight to the CAN communication which is being used to send the commands to the control system of multi-pressure system. The analysis to ensure either the system works as it is supposed to work or not are presented in this chapter. Chapter 4 presents measurements results.

Chapter 5 presents the energy consumption analysis between multi-pressure system and conventional system. The last chapter presents the conclusion of research work and recommendations for future work are provided there.

The target system of thesis work is a JCB 8008 CTS micro excavator shown in Figure 1.1. It consists of 4 actuators. In this thesis work the multi-pressure system is implemented on only one actuator to perform the swing operation. This system has modified load sensing (MLS). Details about MLS are presented in chapter section 2.3. The installation and testing of multi-pressure system is performed at Fluid Power laboratory of Aalto University.

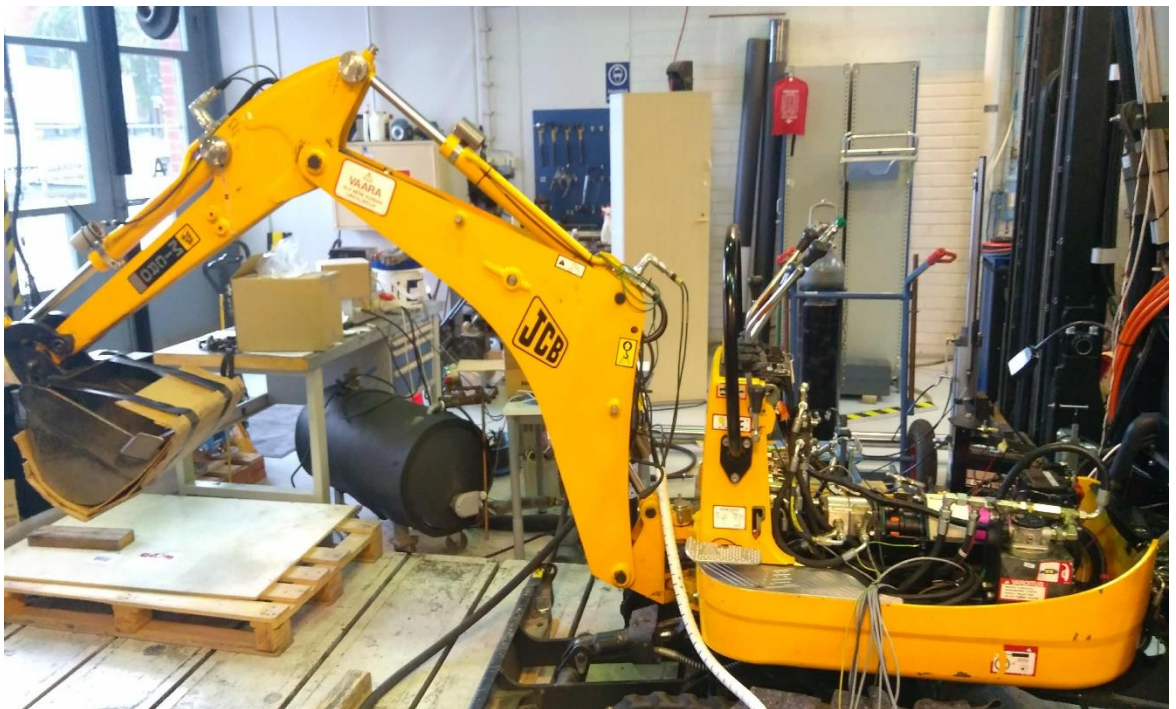


Figure 1.1. *Excavator Test rig*

2 LITERATURE REVIEW

2.1 Energy Efficiency of Hydraulic System

Excavators are back bone of construction industry. Hydraulic supply unit is the main power supply unit in excavator. The power supplied by hydraulic system is used to control force and movements of actuators. The hydraulic systems are considered less energy efficient when compared with electrical and mechanical systems. Energy efficiency of the hydraulic system is compromised because of throttling and diesel engine losses, one recent trend is to improve it. The parallel focus of research is also to reduce particle emission and fuel consumption of diesel engine.

Rydberg [5] found that the efficiency of mobile load sensing system can reduce to 20% efficient for lifting application. A big portion of power losses in LS comes from the throttling in the valves. A valve is an important component of a hydraulic system as it matches the supply pressure with the load pressure of actuator. Study found that 30% of the energy losses are because of the valves only [5]. The reason of energy losses in the valves is huge pressure drop across the valve in a load sensing system.

Considerable amount of efforts is put to decrease the energy losses in the valves. These studies seem promising and implementation of these technologies have the potential to reduce the power losses in hydraulic system. Studies are done either to reduce the usage of the valves or to implement the digital hydraulic independent metering valve systems. The concept behind implementing the digital hydraulic independent metering valve systems is to optimize the usage of the valves to decrease the pressure losses. The pressure losses because of throttling are also called system inherent pressure losses (SIPL). SIPL is prominent in a system where multiple actuators are operating simultaneously at different pressure levels [6].

Diesel engine (prime mover) causes the pump to rotate. The efficiency of engine is at its best just over 40%. It also provides power to some additional subsystems which causes extra losses [7]. Pump supplies pressurized fluid to the actuators. In an excavator different actuator require different pressures which depend upon the load condition of actuator. Load sensing technique makes sure that pump can supply adequate pressure to actuator which has greatest load pressure. The supplied pressure by the pump is too high for other actuators (which have lower pressure demand). Pump supplies the pressure greater than the required pressure because some pressure will be dropped in pipes, hoses and especially in directional control proportional valves. Pump and diesel engine

are designed according to the peak power requirements of actuators. Thus, pump and diesel engine are typically dimensioned for larger power needs than the average power consumption. Recent trend of research is to reduce the fuel consumption and particle emission of diesel engine. Studies have found that it is possible to implement small size diesel engine by installing local pressure sources and energy recovery systems.

Prime mover and valves are major causes of power losses in valve controlled hydraulic system. The causes of power losses are explained in detail. Rydberg [5] presented that piping system contributes 10% of power losses and mechanical losses contribute 15% of the losses in a typical mobile load sensing system for lifting application. If the idling losses are also considered, then the energy efficiency is almost 20%. The power losses for this specific application are shown in Figure 2.1.

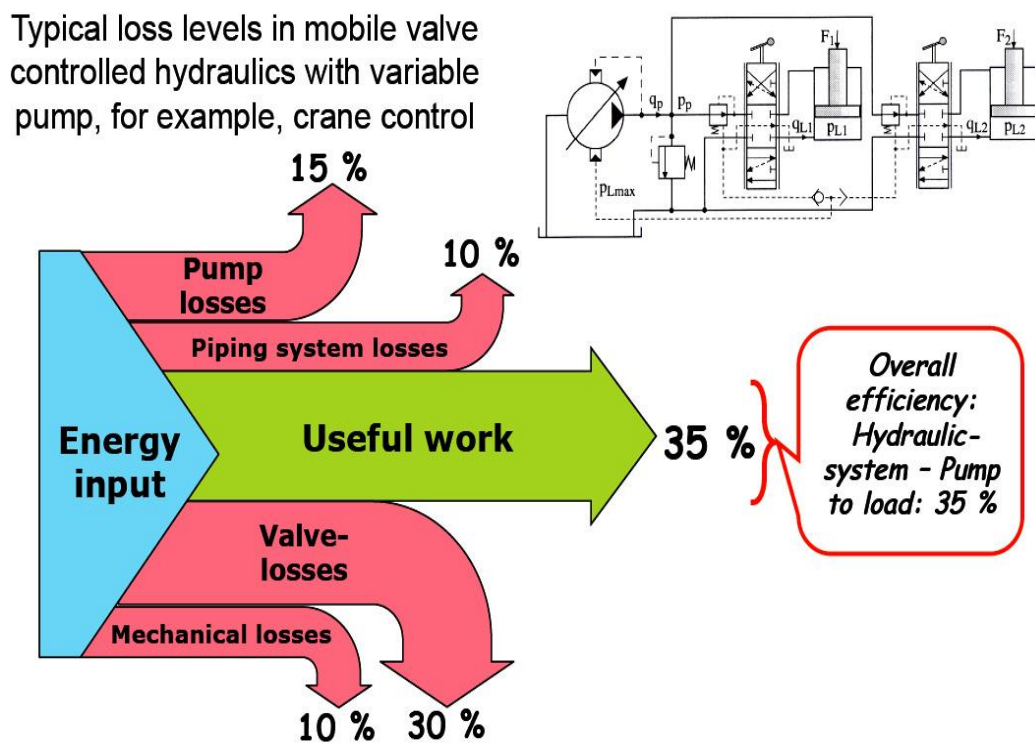


Figure 2.1. Losses in Valve Controlled System [5]

2.2 Load Sensing Hydraulic System

Load sensing (LS) is the most common technique used in mobile machines for hydraulic power transmission. LS replaced the conventional fixed-displacement pump system (FDPS) which provides the constant flow to the system. The actual problem with this system is that in lower load pressure conditions the excessive flow is released to tank via pressure relief valve (PRV). This causes tremendous amount of losses in form of heat across the PRV. So, in practical situations when the load is varying this system is

not efficient. Specifically, if we consider the excavator mechanism, where the load is varying in each working cycle. Circuit diagram of FDPS is shown in Figure 2.2.

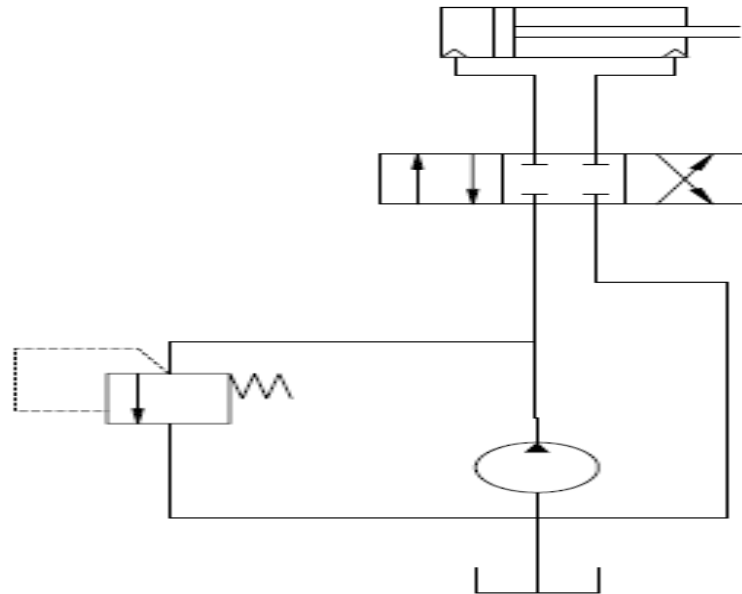


Figure 2.2. Fixed-Displacement Pump System

The exclusive feature of LS is that it provides the pressure according to actuator's load pressure requirement. The basic architecture of LS is just like a feedback control system. This approach seems promising because the actuator gets the required pressure, so less pressure drops across the valve which means less power losses.

LS consists of variable displacement load sensing pump, a compensator block and load sensing directional control valve. Compensator block is combination of pressure-flow compensator (PFC) and high-pressure compensator (HPC). The swashplate of the pump is controlled by compensator block to produce flow needed to provide the pressure required by LS system. The pilot line of PFC is connected to the inlet port of the cylinder to sense the load pressure requirement of the actuator. If more pressure is required then PFC directs the swashplate to generate more flow, which causes more pressure. When the system pressure rises then high-pressure compensator (HPC) directs the swashplate control piston to reduce the flow to the system. In this way LS supplies the required pressure to system. Circuit diagram of LS system is shown in Figure 2.3 [8].

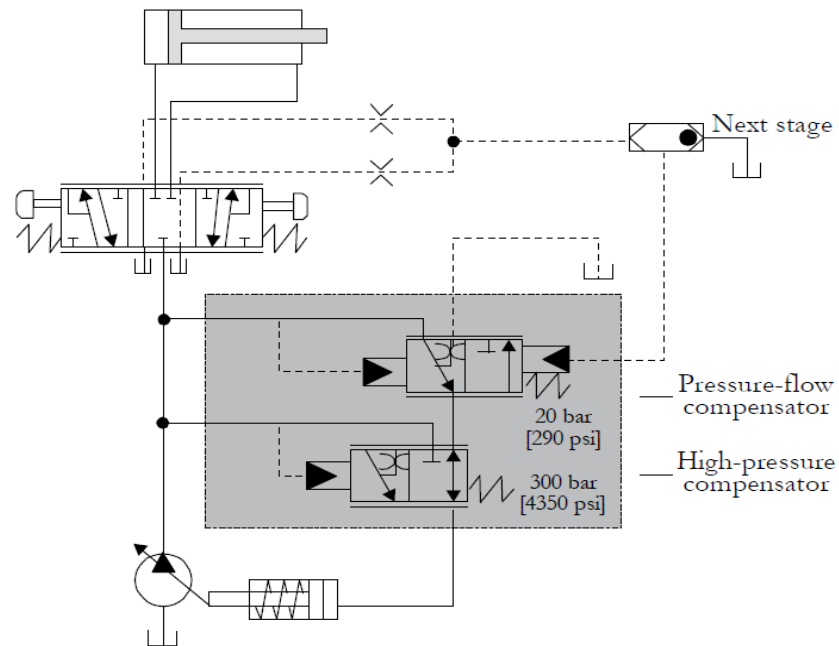


Figure 2.3. Load Sensing System [8]

LS technique seems efficient as the excessive flow to the system is reduced significantly. It works well for a single actuator. What will be the scenario when there is more than one actuator?

Excavator has single power source and multiple actuators. It is also known as single pump/multiple load system. Typical hydraulic system of a mobile machine is shown in Figure 2.4.

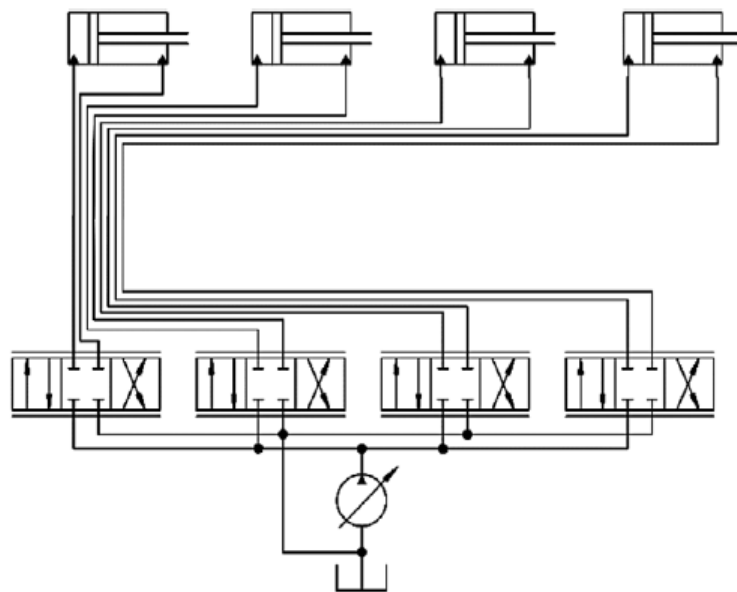


Figure 2.4. Typical Hydraulic System of Excavator [9]

Figure 2.4 shows that system has one power source, four valves and four actuators. LS senses the load pressure at each actuator. The highest pressure required is fed back to pump. Pump supplies the pressure which the actuator with the highest load pressure requires. Now, the pressure requirement of each actuator is different. Some actuators may require very low pressure as compared to the highest pressure. As a result, the pressure drop across the valve with least required pressure is maximum and ultimately power losses are maximum. Similar situation is for the rest of two actuators which do not require maximum pressure. So, LS is only efficient for one actuator which requires maximum pressure while it is inefficient and causes big power losses for remaining three actuators which have low pressure requirement. In this way cumulative energy losses are huge.

2.3 Modified Load Sensing System of Micro Excavator

In this thesis work JCB 8008 CTS micro excavator is used. Danfoss PVG32 directional valves are used in this excavator. The system differs from the industrial excavators because diesel engine is replaced with a 10-kW electric motor which is controlled by. Sevcon Gen4 controller. The electric motor is powered by four lead-acid batteries. One drawback of using these batteries is that operating time of the machines is less compared to diesel engine. The operating time can be increased by using the large size batteries.

The LS system used in this micro excavator is different from the typical LS system. To keep it clear LS is termed as modified load sensing system (MLS). This micro excavator has two fixed volume gear pumps. These pumps are connected to motor shaft through a coupling and with a torque sensor. The directional control valves are connected to actuators. These control valves are Sauer Danfoss PVG32. PVG stands for proportional valve group. These valves have three modules: pump side module (PVP), basic modules and actuation module. The load pressure of the actuator is continuously sensed by the pressure adjustment spool (PAS) (6) through load sensing channel. The purpose of PAS is also to adjust the pressure of system. The load sensing channel is shown with dotted lines in the Figure 2.5. If the spools of directional valve are neutral, then pressure adjustment spool (6) is open. In this case the flow is directed towards the tank. When one of the spools of directional valves is actuated then, pressure in load sensing channel reaches to highest pressure and PAS maintains a constant pressure difference between load and system pressure. Load-sensing circuit connects with actuated port and shuttle service circuit selects the highest load pressure port [10].

The schematic diagram of modified load sensing system is shown in Figure 2.5.

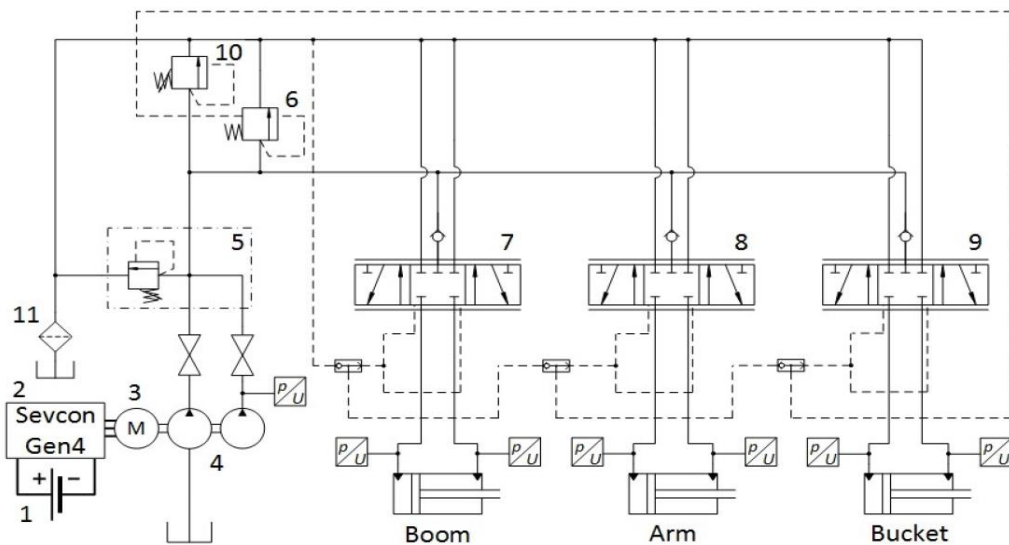


Figure 2.5. Modified Load Sensing System [10]

2.4 Studies to Improve the Efficiency of Hydraulic System

During recent years numerous approaches towards the energy-efficient hydraulic system have been studied.

Concept of secondary controlled multi-chamber hydraulic cylinder is introduced by Linjama. This approach seems promising as author claims that practically it has no throttling losses. This concept has been implemented on a 30-ton excavator and results are encouraging. Studies found that power losses are reduced about 60% compared to traditional load sensing system [11].

Ketonen applied a digital independent metering valve (D-IMV) system to a 20t excavator. D-IMV has four (4) independent controlled metering edges for each actuator. These metering edges are made up of a series of parallel connected on/off valves. This system has ability to optimize the pressure losses of metering edges. Author compared the energy consumption of D-IMV with the traditional load sensing. It was found that input energy is reduced by 28-42% compared to LS [12].

Milos [7] introduced a novel fuel consumption model for a diesel engine which can be utilized in mobile machines. In this approach author classified the fuel consumption into fix and variable components. The model was validated on real test data from an 18t excavator.

Andera presented a hydraulic hybrid excavator mechanism. The author combined the energy saving concepts like dual LS pump, pump margin reduction and energy recovery

systems. It was suggested that potential energy can be recovered during actuator's lowering phase. An energy recovery system composed of hybrid control valve, a hydraulic accumulator, a hydraulic motor and an electronic control unit was also introduced. Author presented a hybrid solution based on these techniques. This was designed by keeping in mind the pros and cons of different techniques. The simulation results showed 15% less fuel consumption for digging cycle. This hybrid solution reduces the energy losses in components, the most prominent is 70% reduction in local pressure compensator (LPC) [13]. The concept is still waiting to be implemented on a real excavator but so far, the results are promising.

Jan proposed optimized load sensing technique to reduce SIPL. In this technique concept of Tank/Accumulator Logic Valve (T/A-LV) is introduced. T/A-LV connects the return line with the tank or accumulator depending upon the load pressure situation of actuator. This approach reduces the SIPL up to 44% as compared to traditional load sensing technique [6].

Salomaa analysed the energy efficiency of micro excavator by implementing the concept of direct driven hydraulics (DDH). Research show that required input energy decreases up to 91.6% compared to MLS. DDH is a promising technique to get rid of the power losses generated by valves because the preliminary focus of DDH is to introduce a system without valves. In this technique the pump is operated by variable speed electric motor. In this way the flow to the actuator from the pump is controlled. DDH has potential to increase the overall efficiency of the system up to 71.3% in the studied case. In this study the power source is an electrical battery and prime mover is an electric motor instead of diesel engine. The hydraulic system for comparison is not pure LS but a modified form of it (MLS) [10].

Linjama introduced the concept of multi-pressure hydraulic actuator. This approach is introduced to improve the energy efficiency of hydraulic components and to decrease the dynamic requirements of prime mover. The idea in this study is to connect the various pressure sources with cylinder chambers via on/off valves. The results of this study are promising because the power losses are 77% less than in traditional load sensing technique in the studies case [9].

As discussed earlier the focus of the researchers is steered towards the hybridization to have an ideal system. In this thesis an ideal system is defined as a system which has maximum energy efficiency, reduced pressure losses and less fuel consumption.

The three most promising techniques are discussed in detail in this research work. These techniques are termed as most promising because implementation of these techniques

has significantly improved the energy efficiency as well as fuel consumption of system. Secondary controlled multi-chamber cylinder and multi-pressure hydraulic system's efficiency is compared with the conventional load sensing system. Direct driven hydraulic system's efficiency is compared with modified load sensing system.

2.5 Promising Energy Efficient Techniques

Numerous technologies developed by researchers have potential to improve energy efficiency of hydraulic system. In this thesis work the most advanced studies are discussed in detail. The application of these technologies to be presented is not the same. Multi-pressure system and multi-chamber hydraulic cylinder is implemented on a boom mock up system and the energy efficiencies are compared with the conventional load sensing system. The DDH system is implemented on a micro excavator and energy efficiency is compared with the modified load sensing system. Multi-chamber cylinder and DDH systems are valve-less systems. The multi-pressure system consists of number of on/off valves. Work cycles and energy consumption is different in each application that is why these technologies are not fully comparable.

The potential of power loss reduction with these techniques is compared with the LS technique. Multi-chamber hydraulic cylinder has been implemented on an excavator. Multi-pressure hydraulic system is tested so far on boom mock-up system. This system is implemented for the first time on a real excavator in this thesis.

One thing should be noticed that these applications are not fully comparable because the system structure, work cycles and energy usage is different in each case. In the studied case DDH improves the energy efficiency of MLS up to 71.3%. Multi-chamber hydraulic cylinder reduces power losses up to 60%. Multi-pressure hydraulic system reduces the power losses up to 77%. A brief insight to these technologies is provided in the subsequent chapters.

2.5.1 Secondary Controlled Multi-Chamber Cylinder

The multi-chamber actuator comprises a set of individual single chamber systems, mechanically linked together through a moveable piston. This cylinder consists of four chambers. Chambers A and C provide extension while chambers B and D provide retraction. The structure of a four-chamber cylinder is shown in Figure 2.6.

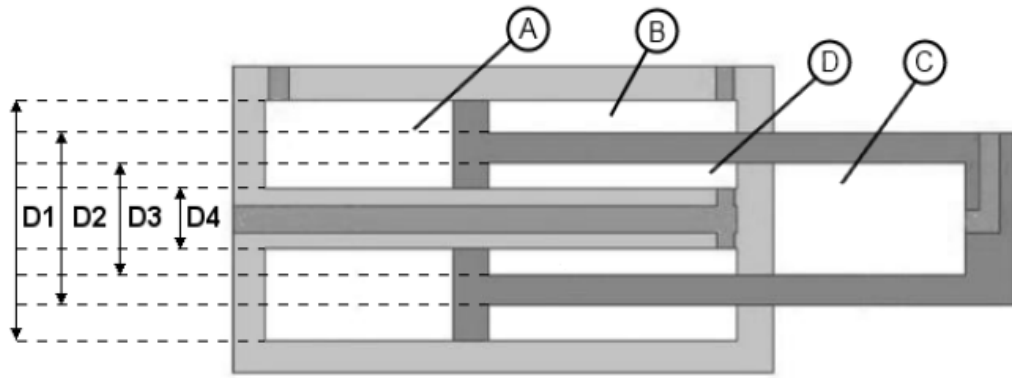


Figure 2.6. Structure of a Four Chamber Cylinder [14]

Kim [15] compared the base line excavator system with the hybrid excavator system based on multi-chamber cylinders and hydraulic accumulators. The proposed hybrid excavator is different from the baseline excavator since it has the ability to recover energy from the overrunning loads. The recovered energy is stored in the accumulator.

Secondary controlled multi-chamber hydraulic cylinder is used to produce discrete forces. Linjama [11] studied the use of four-chamber cylinders in which each chamber of the cylinder is connected either to tank line or supply line via on/off valves. Sixteen different force combinations are available. This can be considered as a force actuator with 16 discrete output values. This approach seems promising because it avoids the unnecessary throttling losses. It reduces the power losses up to 60% compared to traditional load-sensing system in the studied application. Multi-chamber cylinder with on/off valves is shown in Figure 2.7.

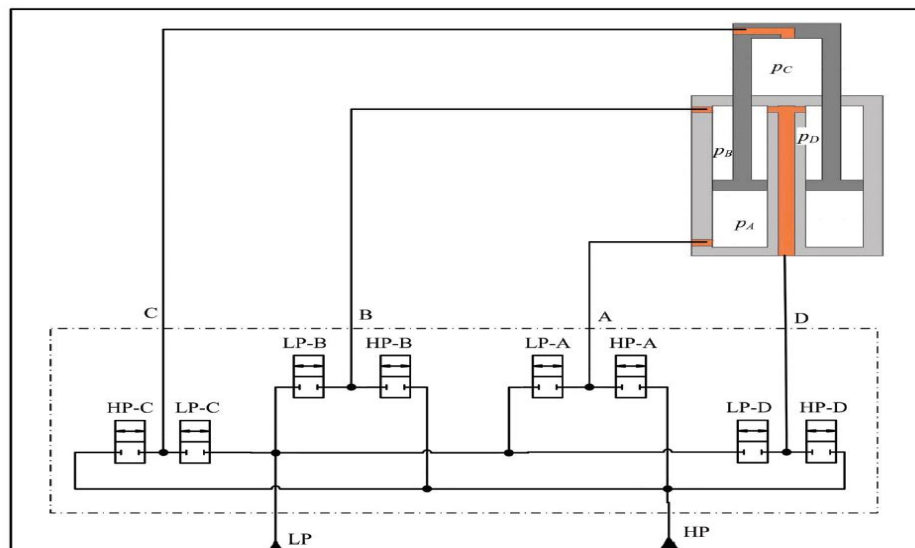


Figure 2.7. Multi-chamber cylinder with on/off valves [11]

Kim [16] implemented the concept of multi-chamber cylinder with hydraulic accumulators to reduce the fuel consumption of a Volvo 30 ton wheel loader. Inclusion of hydraulic

accumulators make it possible to recover potential and kinetic energy. Energy can be recovered during boom's downward motions and swing deceleration. Study showed that this approach has the potential to reduce the fuel consumption up to 20%.

2.5.2 Direct Driven Hydraulics

In Direct Drive Hydraulic (DDH) system an electric motor is directly connected to one or more pumps to control the flow and actuator motion. In a studied case [10] motor is coupled with two pumps via a common shaft. Pumps are connected to chambers of cylinders and reservoir. Pump controls the linear motion of cylinder and pump itself is controlled by an electric motor. In conventional centralized hydraulic system pump supplies the pressurized fluid to actuator via hoses. The distance between the pump and actuator can be long in conventional hydraulic system which requires long hoses. DDH technique decreases the amount and length of hoses in the system because it does not include valves between pump and actuator so it can be installed close to actuator. An ideal way to pass the fluid from pump to actuator's chamber and back to reservoir is achieved. In conventional hydraulic system the fluid passes through the hoses, valves and then goes into tank. The ratios of the pump displacements and cylinder chamber areas should match with each other. If there is a mismatch between the corresponding displacements of the pumps and chambers areas, then excess pressure rises in chambers and degrades the system's efficiency [17]. The simplified hydraulic schematic of DDH system for an excavator is shown in Figure 2.8.

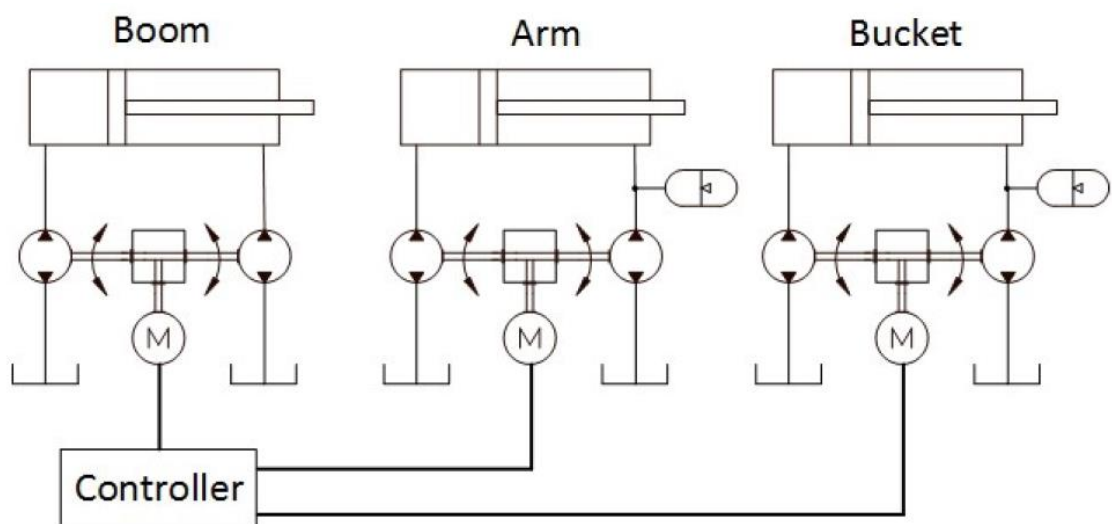


Figure 2.8. Hydraulic schematic of DDH system [10]

In hydraulic systems backpressure is generated because the return flow passes through hoses and valves. Backpressure reduces the energy efficiency of hydraulic actuator because it causes an opposing force. DDH system removes the directional valve from this system and decreases the amount and length of hoses to reduce the effect of backpressure. This is a smart way to improve the efficiency of system as a study [10] shows that directional valve group causes almost 60% of power losses in conventional hydraulic systems. However, friction losses in the hydraulic cylinder in the studied case are 33% which can be improved to make it more efficient.

2.5.3 Multi-Pressure Hydraulic System

Multi-pressure actuator is a new concept to improve the energy efficiency and decrease the power losses in hydraulic systems. It consists of an accumulator, an actuator and on/off valves integrated with control unit. The idea behind the concept is to make the transformation of hydraulic energy into mechanical work more efficient in terms of energy losses and power requirements. This new technique is capable of energy regeneration because it has means to store potential and kinetic energy and utilize them. In a multi-pressure system, a number of different pressure sources are available to the actuator. Accumulators store the hydraulic energy locally and provide the pressure to the actuator according to its instantaneous demand. The accumulator provides instantaneous hydraulic power required instead of pump and motor/diesel engine. Accumulator also helps to optimize the operating point of pump which doesn't only improve the efficiency of pump but also enhance the efficiency of overall system. The convertor cylinders provide discrete pressures and in this way number of different pressures are available to the actuator. The on/off valves are used to connect the chambers of actuator to the suitable pressure sources [9]. Power losses in different components of multi-pressure hydraulic system are shown Figure 2.9. [18].

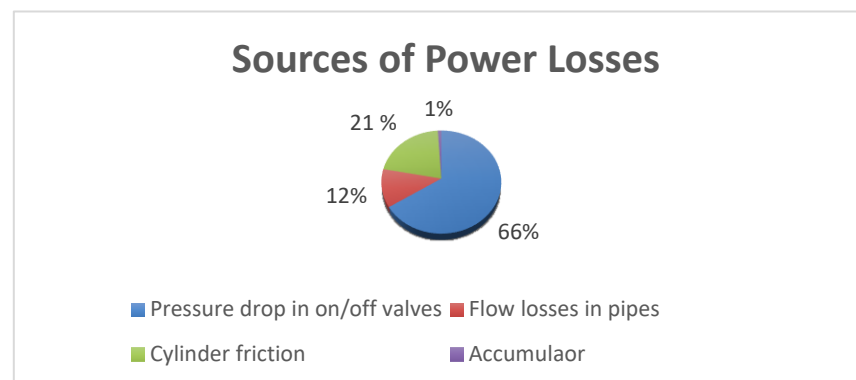


Figure 2.9. Sources of Power Losses in Multi-Pressure System

2.6 Brief Introduction of Multi-Pressure System

The concept of multi-pressure system was introduced to decrease the throttling losses and to downsize the pump and diesel engine. In LS system throttling losses occur when the supply pressure is matched to load pressure. The matching of pressure in LS systems requires a constant pressure difference between the pump and actuator which means a substantial power loss. These losses are emphasized when multiple actuators are in operation and pressure requirement of each actuator is different. In mobile hydraulics diesel engine is the main power source to the hydraulic system and it is dimensioned in LS system according to the peak power requirements. This is necessary because in various load cycles power taken from the diesel engine is higher than the mean power. Diesel engine supplies mechanical power to the pump and it supplies hydraulic power to actuator. If the power requirement of the actuator fluctuates, then also the power supplied by diesel engine will change rapidly which increases the fuel consumption and emissions. Moreover, the efficiency of diesel engine is just 40% at optimal operating point. The throttling losses and diesel engine losses reduce the overall efficiency of power transmission system. Although there are also power losses in other components of a hydraulic system but these two are typically the major contributors to power losses in traditional hydraulic systems.

The multi-pressure system has the potential to resolve the afore-mentioned problems and to improve the energy efficiency of a hydraulic system. To decrease the throttling losses concept of multi-pressure system comes up with an idea to have multiple pressure sources in a system. As the load pressure requirements of an actuator vary, actuator should be supplied with the exact required pressure. The layout of this concept is presented in Figure 2.10. Pressure sources are connected to chambers of cylinders via on/off valves. The actuator has discrete pressure sources available. The chambers of cylinder can be connected to suitable pressure sources to have minimal pressure drop across the valves. Figure 2.10 presents the basic concept of multi-pressure system in which hundred pressure sources are connected to actuator. In this way system has 10,000 combinations of available pressure sources. This approach can reduce the throttling losses significantly. The next target is to reduce the power losses of diesel engine and to implement the small size diesel engine. How this approach can help to achieve it is explained in next paragraph.

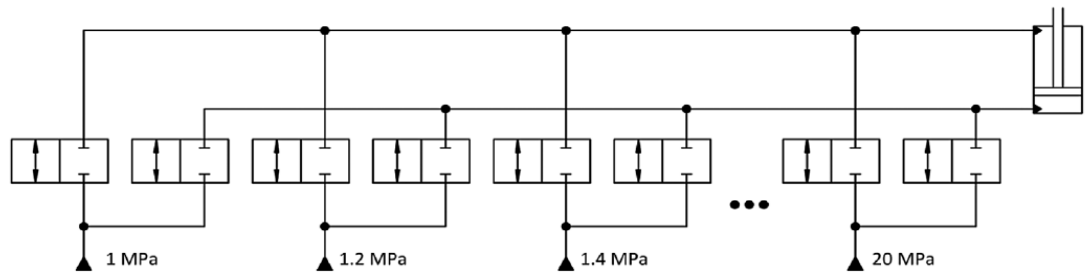


Figure 2.10. Basic Idea of Multi-Pressure System [9]

The typical lay out of hydraulic system in an excavator is shown in Figure 2.4. A variable displacement pump supplies power to four actuators. These actuators are connected to four directional control valves. The pressure drops across the valves cause huge power losses. In this system power taken from the diesel engine is coupled with the output power of the actuator. As mentioned earlier the diesel engine and pump are dimensioned according to the peak power requirement of the actuator. Multi-pressure system comes up with a solution in a way that a local energy storage unit is integrated with each actuator. The actuator has discrete combinations of pressures available and only the required pressure is supplied to actuator. The pressure drop across the on/off valve is small as compared to proportional valves used in LS system. The mean power is supplied by the pump while the power fluctuations are handled by that integrated power source. This concept was presented by Linjama [19]. In this way the power taken from the diesel engine is not coupled with the actuator. The diesel engine will supply the power according to mean power requirement of the system. So, the pump and diesel engine can be dimensioned according to mean power requirement. This will help to implement the small size diesel engine and pump in system. Ultimately fuel consumption and cost of the system design is decreased. Huova presented the experimental test system of a multi-pressure system. In this setup the main source of the power is an electric motor instead of diesel engine. The system consists of a high-pressure accumulator, four asymmetric cylinders, a pump and a motor. In this way six pressure sources are available to the system [9]. Chambers A and B of actuator are connected to pressure sources via on/off valves. In this system a local hydraulic energy storage is located together with actuator. Exclusive feature of this system is that actuators and supply systems are integrated into one unit which makes the installation of it easy in industrial and mobile hydraulics. The centralized pump is designed according to mean power of the actuators. The actuators are connected to a single high-pressure line and a single return line. Schematic diagram of multi-pressure system designed by Huova is shown in Figure 2.11.

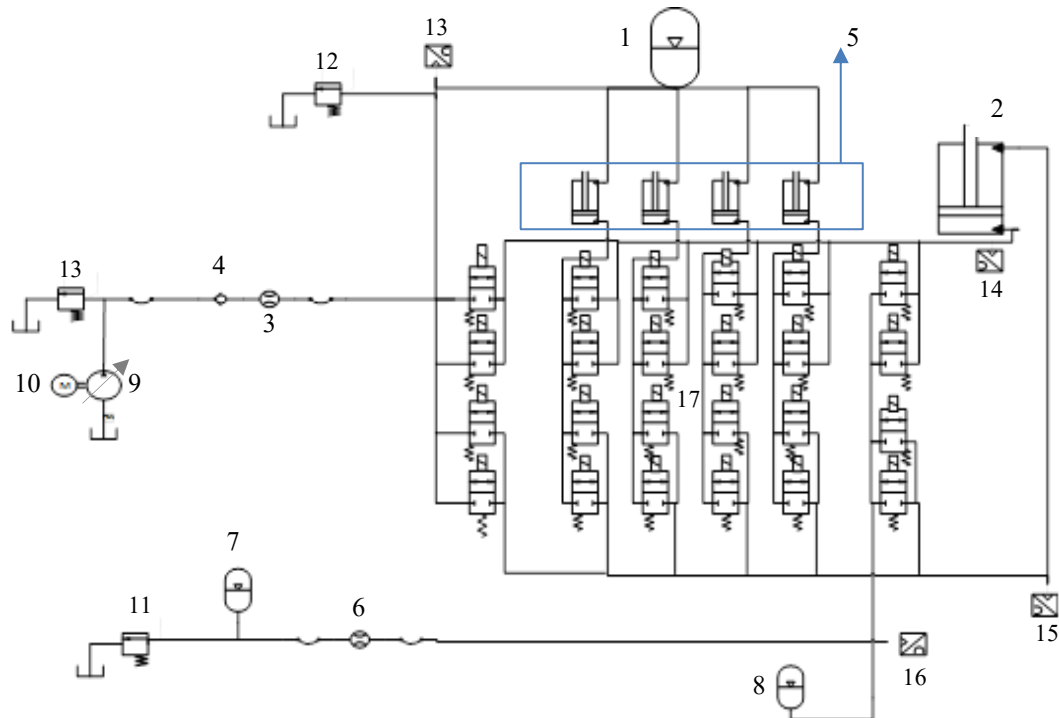


Figure 2.11. Multi-Pressure Hydraulic System

Table 2.1. Description of Multi-Pressure Hydraulic System's Components

Sr. No.	Description	Details
1	High Pressure Accumulator	2 liters
2	Swing Actuator	52/25 - 293mm
3 & 6	Flow Sensor	Kracht VC 0.4 -VC 1
4	Check valve	HBS ½" 0,5 bar
5	Pressure converters	50/40-120 mm 50/36-120 mm 50/30-120 mm 50/22-120 mm
7 & 8	Low Pressure accumulator	1 liter
9	Dual Pump	Parker PGP511 (2* 6 cm ³ /r)
10	Electric Motor	10 kW
11, 12	Pressure relief valve	Rexroth VSC-30
13,14, 15, 16	Pressure sensor	Trafag NAH 8254
17	Doubled 2/2 on/off-valves	Bucher W22-D-5

2.7 Operation Principle of Multi-Pressure Hydraulic System

Multi-Pressure system has 6 distinct pressure sources available for actuator. These pressure sources are one pump, one high pressure accumulator and four pressure converters. To understand the operation principle of system, working principle of each pressure source is explained in following paragraphs.

A model-based force controller is used in this thesis work. The details of model-based force controller are explained in research work of Huova [20]. Different force combinations are available and controller selects the force combination which have minimum error between the reference and measured force signals. Possible force combinations for this study case are presented in Figure 2.12.

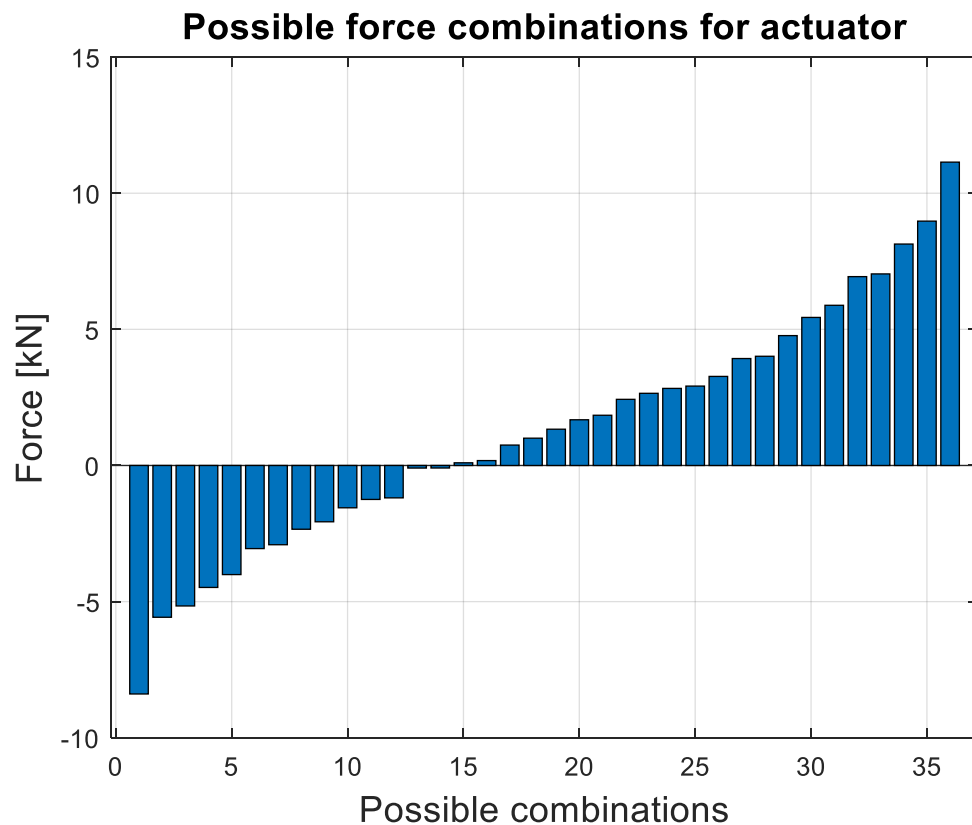


Figure 2.12. Force Combinations for Actuator

Electric motor is prime mover in this study case. The on/off operation of the motor is controlled through the controller. Pump is coupled with an electric motor through a shaft. Purpose of the pump is to provide the pressurized flow to the accumulator. When the electric motor turns on it causes the pump to rotate. The motor turns on only when the pressure in the accumulator is lower than the 4.1 MPa and turns off when pressure reaches to 5.3 MPa. Hence, purpose of the pump in multi-pressure hydraulic system is to supply pressurized fluid only to the accumulator.

High pressure accumulator is filled with the pressurized fluid supplied from the hydraulic pump. The pressurized fluid from the accumulator is provided to the actuator's chambers through on/off valves. The controller controls the opening/closing of the on/off valves in such a way that the switching behavior of the valves is moderate.

In a multi-pressure system there are four small asymmetric cylinders. These cylinders act as pressure converters between the high pressure accumulator and the actuator. The pressurized fluid from these pressure converters is supplied to actuator through on/off valves. The piston size of each cylinder is same but rod size is different. The different rod sizes provides four different pressure sources available to the actuator. There are inductive sensors which measure the positions of these pistons. The controller prevents these pistons to hit the end positions. In this way the position of converter cylinders is controlled.

3 IMPLEMENTATION OF MULTI-PRESSURE SYSTEM

3.1 Experimental Setup of Multi-Pressure System

The implementation of multi-pressure system is conducted at Fluid Power laboratory of Aalto University. The purpose of this thesis work is to install the multi-pressure system and measure the power and energy consumption for the swing operation of excavator when it is subjected to high and low inertia.

Block diagram of multi-pressure system experimental setup is shown in Figure 3.1.

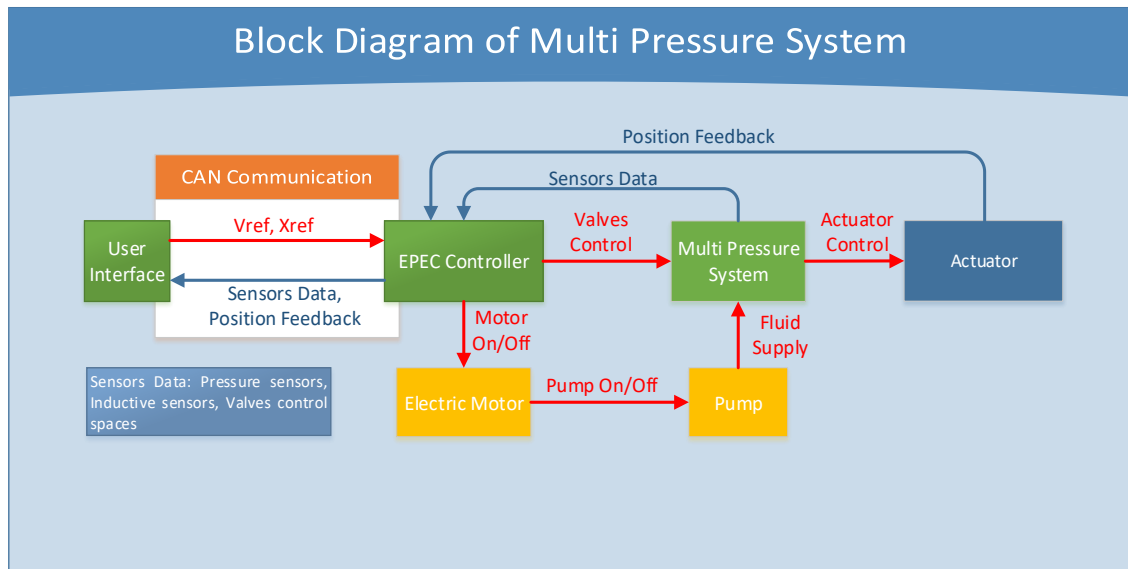


Figure 3.1. Block Diagram of Multi-Pressure System

Initially assembly of hoses, flow sensors, check valves, pressure relief valves and tank line accumulators were installed. The system has two flow sensors, one for the measurement of pump flow rate and other flow sensors in the tank line is to measure the tank line flow rate. Pressure sensor to measure the pressure of pump was already installed. Finally, the package of multi-pressure system was mounted on mini excavator and pressure line and tank line connections were assembled. This package comes with the pre-installed pressure sensors and inductive sensors. The exclusive feature of the system is that it has integrated valves and electronics. Position sensor is used to measure the position of actuator. Pressure sensors are used to measure the pressures in cylinder chambers and accumulators. Inductive sensors are used to measure the position of pressure transformer cylinders. EPEC 5050 as CAN control unit system is used to control

these sensors. It has 32-bit CPU and 65 I/O pins. It is in small size and weighs 0.95 kg. The installed package on excavator is shown in Figure 3.2.

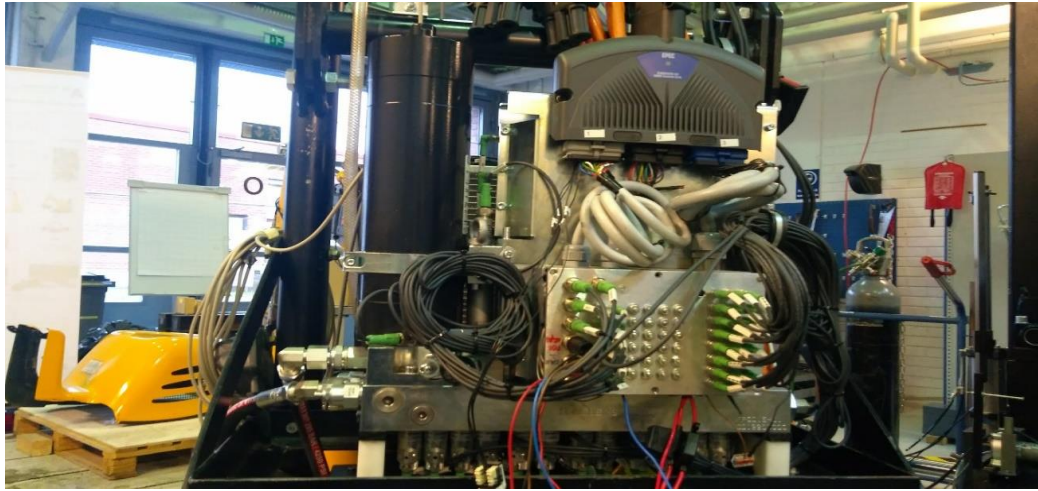


Figure 3.2. Multi-Pressure System mounted on excavator

CAN bus communication is used in this thesis work. CAN interface is according to ISO 11898 and CAN 2.0B protocol. CAN communication system was already developed to communicate with the EPEC controller of multi-pressure system. PCAN-USB adapter is used for CAN communication. This communication system is developed in the MATLAB/Simulink environment. A graphical user interface is designed. The graphical user interface has been designed to serve multifold purposes. User interface allows the user to run the machine either in auto mode or manual mode. In manual mode user can open/close each valve, change controller's gains and insert either position or velocity references. In auto mode user can not open/close the valves individually but can change the controller gain and insert position/velocity reference. GUI is shown in Figure 3.3.

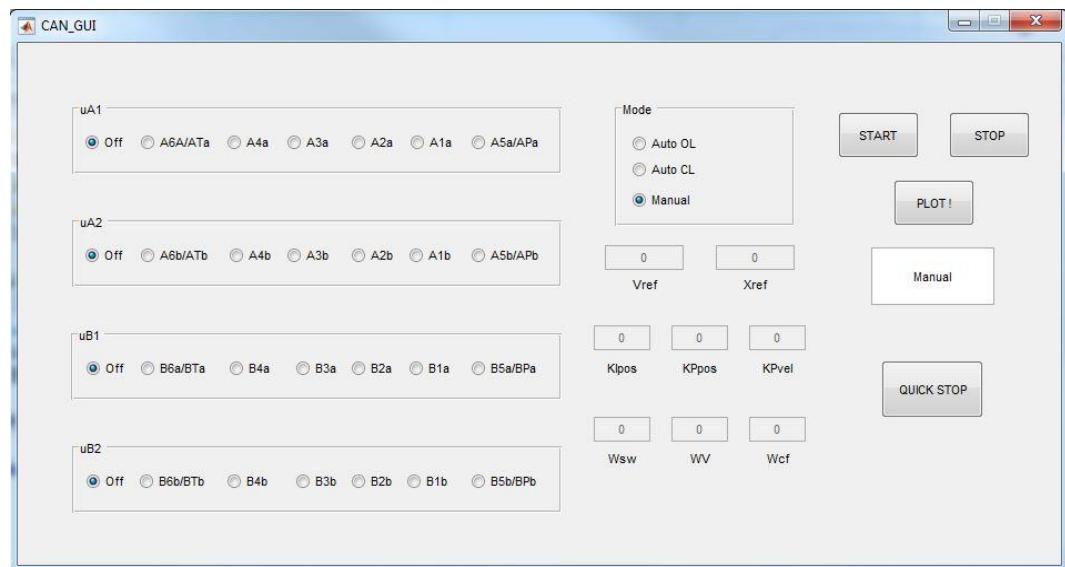


Figure 3.3. Graphical User Interface (GUI)

CAN communications system has transmitting and receiving blocks. CAN transmission block transmits the position reference, velocity reference, valves opening and controller's gain provided by the user as inputs. CAN receiver block receives the information from the system, that information consists of cylinder's chamber pressures, accumulator pressures, valves' opening/closing, inductive sensors output and actuator's force.

3.2 Measurements of the System

The main objective of this research work is to determine the energy efficiency of excavator's swing operation when conventional hydraulic load sensing system is replaced with the multi-pressure hydraulic system. The electrical input energy, mechanical output energy of the motor and hydraulic energy of pump is determined.

The tests are performed to analyse the energy efficiency along with the behavior of the system. First, the tests are performed with the charged accumulator. Accumulator is one of the most important components of the multi-pressure hydraulic system. Accumulator used in this system is 2 liter in size. Pre-charged value of the accumulator is around 4.2 MPa and maximum pressure value is around 5.5 MPa. The gain of the controller is also varied to observe the energy efficiency and system's behavior with high and low gain. So that an optimal gain is selected in which the switching behavior is reasonably good. The criteria to select the best gain is set in which there should be fewer pressure peaks in cylinder chambers', response to the input position reference signal should be reasonable and switching frequency of the valves is reasonable. For the sake of simplicity that gain is termed as default gain in this thesis work.

The pump flow rate is set at 8 l/min during all the tests. The pump is rotated by the electric motor. Pump is operated at lower flow rate than MLS case which means that motor will rotate at low revolutions per minute. Although the motor's efficiency is compromised at lower rotational speed, but for research purpose it is important to lower the pump flow rate to observe that either multi-pressure system is capable to perform the operation with downsized pump and motor or not. The previous tests which were made with the MLS the pump was operated at a flow rate of 18 l/min. The pump flow rate is intentionally reduced more than the half in this research work. The motor is turned on and off through controller. The motor turns on when the pressure in the accumulator reduces to pre-charged pressure value and turns off when the pressure in the accumulator reaches the maximum value. During the tests it is observed that motor does not stop instantly, and it keeps on rotating at very low velocity and takes some time to stop. This behavior of the motor is termed as creeping in this thesis. One reason can be that at lower rpm the controller of the motor does not work well. Due to creeping pump's pressure does not

instantly drops to zero, but it takes some time and then drops to zero. The effect on pump pressure due to creeping is shown in Figure 3.4.

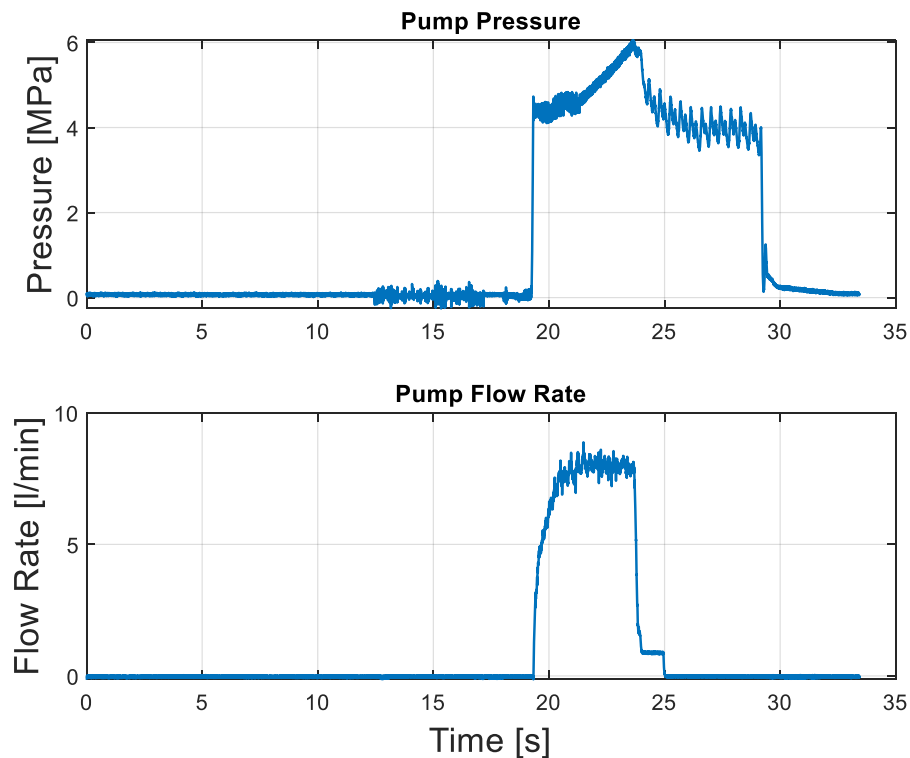


Figure 3.4. Pump Pressure and Pump Flow Rate

When creeping occurs the flow rate from the pump drops to zero, whereas the pressure drops to zero after some time. The electric input power consumed by the motor during the creeping is ignored while doing power calculations. The pump flow rate reduces to zero when the creeping happens it does not affect the hydraulic power calculations of pump as the hydraulic power is product of pump pressure and pump flow rate.

It is observed that when the operation is started with charged accumulator, the system is almost 72% more energy efficient when compared to conventional system. The control behavior of the system is not up to the mark when the system is operated with charged accumulator. The pressure fluctuations in the cylinder chambers are frequent and on/off valves are changing their states quite often. The frequent switching of the valves induces noise and hence reliability concerns.

The tests are also performed with the empty accumulator. The purpose of these analysis is to determine the effects if the operation is initiated with an empty accumulator (hydraulic fluid is released from accumulator). The pressure in the high pressure line is around 1 MPa in this case. With the empty accumulator energy consumption increases because the accumulator has to be charged to generate flow for actuator's movement but the

pressure fluctuations in cylinder chambers reduce when the boom is subjected to high inertia. In case, when boom is subjected to low inertia the pressure fluctuations increases. The detailed analysis when the boom is subjected to high and low inertia are described in subsequent sub-chapters.

3.3 Measurements' Methodology

One of the main goals of this thesis work is to measure the power and energy consumption during the swing operation of the boom. There are two scenarios to perform the swing operation. One scenario is to perform the swing operation with a pressurized accumulator. Another scenario is when the operation is started with an empty accumulator. Initial pressure when the accumulator is pressurized is between 5.2 to 5.3 MPa. When the accumulator is empty the pressure inside the accumulator is around 1 MPa. In each scenario the swing operation is performed in two cases. The first case is when boom length is maximum which means that inertia of the boom is high. The second case is when boom length is minimum which means that inertia of the boom is low.

The proper gain of the controller is selected by observing the switching behavior of the valves. If the valves are switching frequently it shows that these are hyper-active, and controllability is not good. Hyper activeness of valves causes pressure fluctuations in the chambers of cylinder. An optimal gain of the controller is selected in which the switching behavior of the valves is appropriate in both cases of high and low inertia.

Peak electrical input power consumption, mechanical power consumption of motor and hydraulic power consumption of pump is calculated in each scenario. After evaluating the power consumption, the energy consumption is calculated. In each case behavior of the system is studied which includes pressure fluctuations analysis in the cylinder chambers, position trajectory and velocity profile.

3.4 Selection of Controller Gain

The valves schematic of multi-pressure systems used in this study is shown in the Figure 3.5. The valves group PA connects the chamber A of cylinder with the high pressure accumulator. The valves group AT connects the A chamber of cylinder with the low pressure accumulator. Similarly valves group named as PB connects the B chamber of cylinder with the high pressure accumulator and valves group BT connects the B chamber of cylinder with the low pressure accumulator.

Valves in group PA and AT are connected in parallel. These valves are named as uA1 and uA2. Similarly the parallel valves in group PB and BT are named as uB1 and uB2.

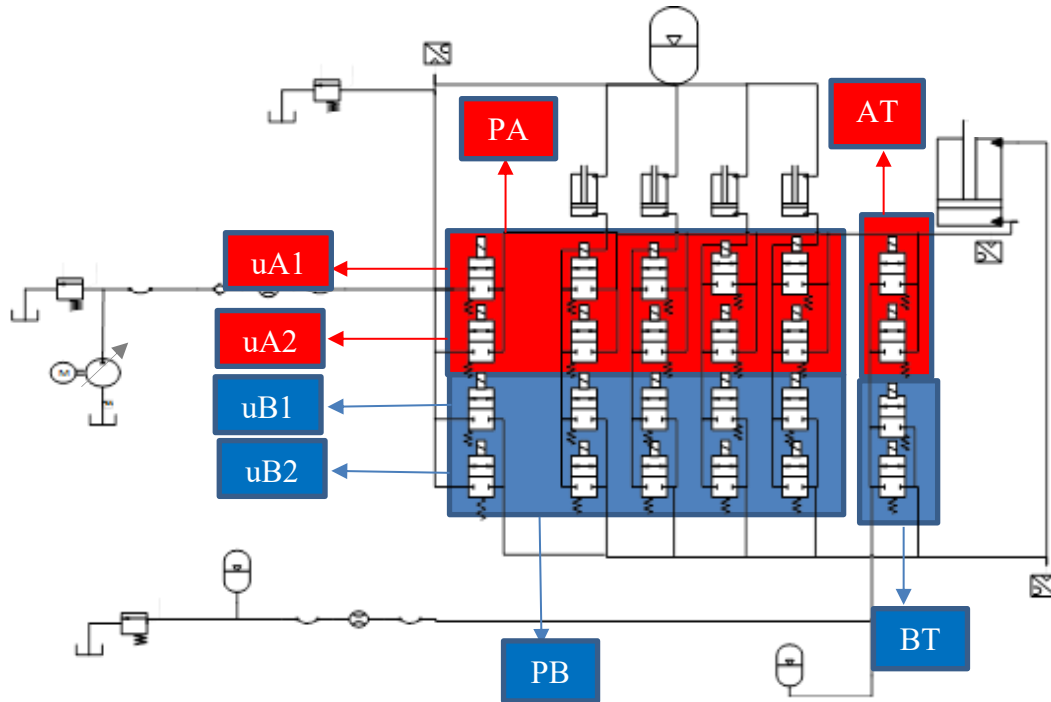


Figure 3.5. Valve Schematic of Multi-Pressure System

The controller of this system is model based force controller. The details of model-based force controller are explained in research work of Huova [20]. It has P controller for velocity and PI controller for position control. The controller gain has a major effect on the usage and switching frequency of the valves. So, the controller gain is critical element for the system's behavior. Controller gain is selected such that valves are not hyperactive, and response of the system is reasonably good. It is observed that for both cases (high and low inertia of boom), the appropriate gain of controller for P controller is 5 and for PI controller is 1.

If the gain is above these values when boom has high inertia, then the valves becomes hyperactive. Figure 3.6 shows the switching of the valves connected to A and B chambers with the selected gain when inertia of the boom is high. States of the valves here means valves opening combinations utilized by the valves.

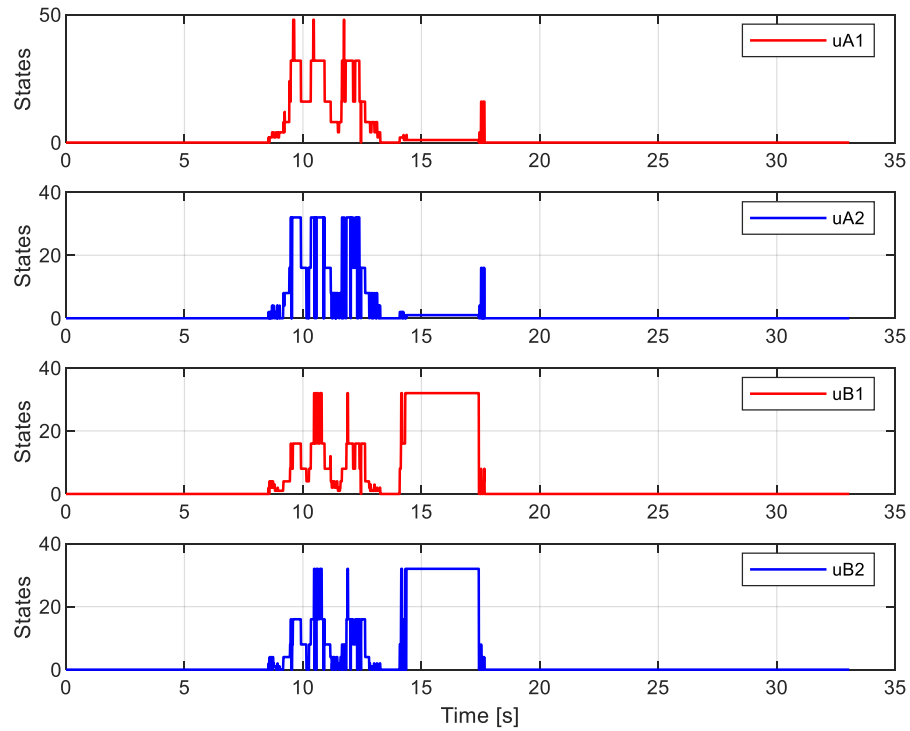


Figure 3.6. *Switching of the Valves with Selected Gain, Case High Inertia*

Figure 3.7 demonstrates the switching of the valves when the gain of the controller is increased further than the selected gain. The switching of the valves is occurring rapidly and the valves keep on switching for a longer period.

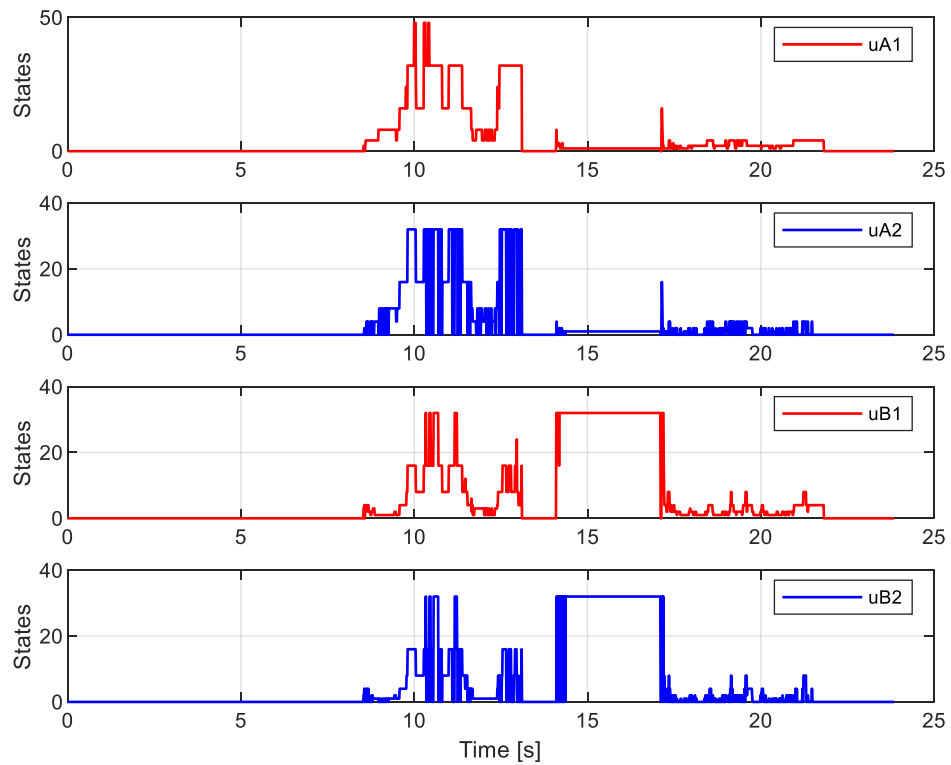


Figure 3.7. *Switching of Valves with High Gain, Case High Inertia*

Position trajectory of cylinder with the selected gain when inertia of the boom is high is shown in Figure 3.8. Position trajectory reveals that there is almost 3 mm position difference between the reference and measured signal at the start and at the end of operation. This difference is because of the pre-defined position tolerance in the software. Figure 3.8 discloses this difference of position between the measured signal and reference signal which causes the measured signal to lag the reference signal. There is a large lag between the reference and measured signals during the retraction phase of cylinder.

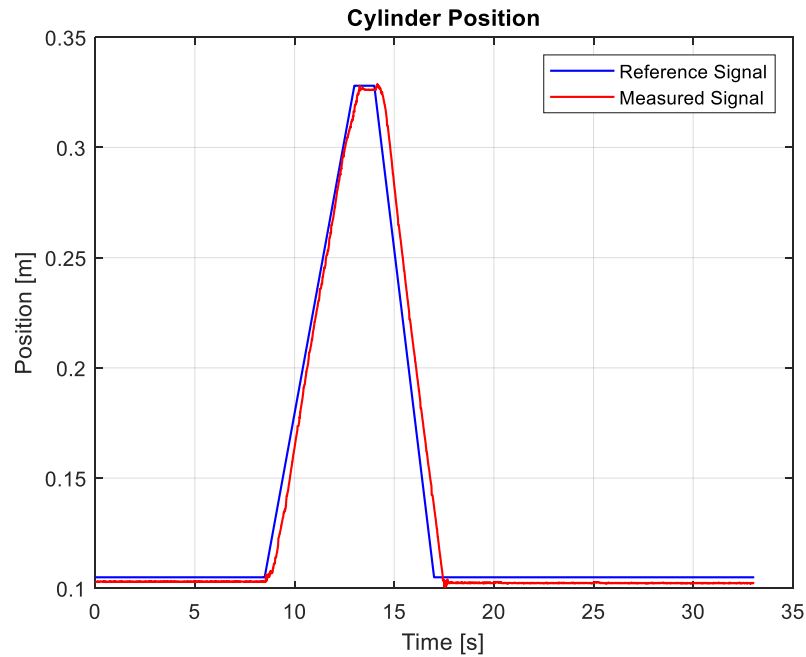


Figure 3.8. Position Trajectory, Case High Inertia

Velocity profile of cylinder's motion when boom is subjected to high inertia is illustrated in the Figure 3.9. The oscillations are high during the extension phase of cylinder motion. The velocity profile during retracting is reasonably good as compared to extension phase of cylinder's motion.

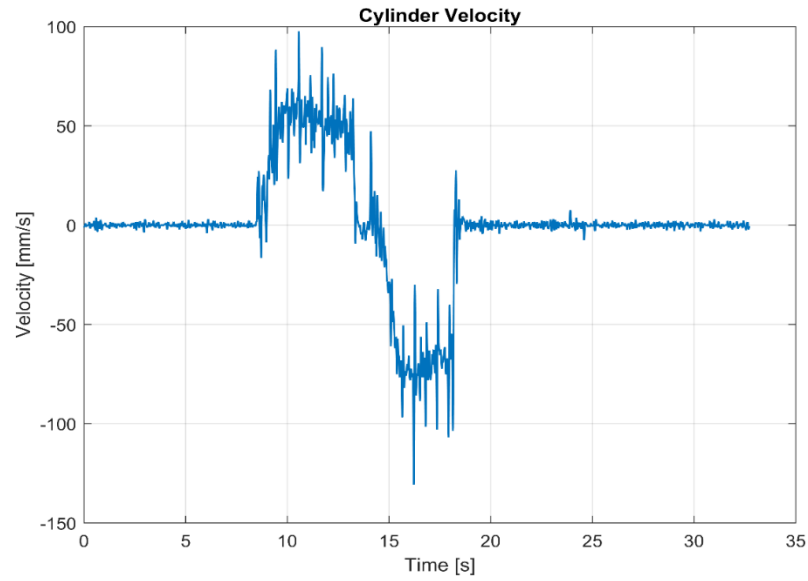


Figure 3.9. Filtered Velocity Profile, Case High Inertia

When the inertia of the boom is low and the gain of controller for P controller is 5 and for PI controller is 1, then switching behavior of the valves is presented in Figure 3.10.

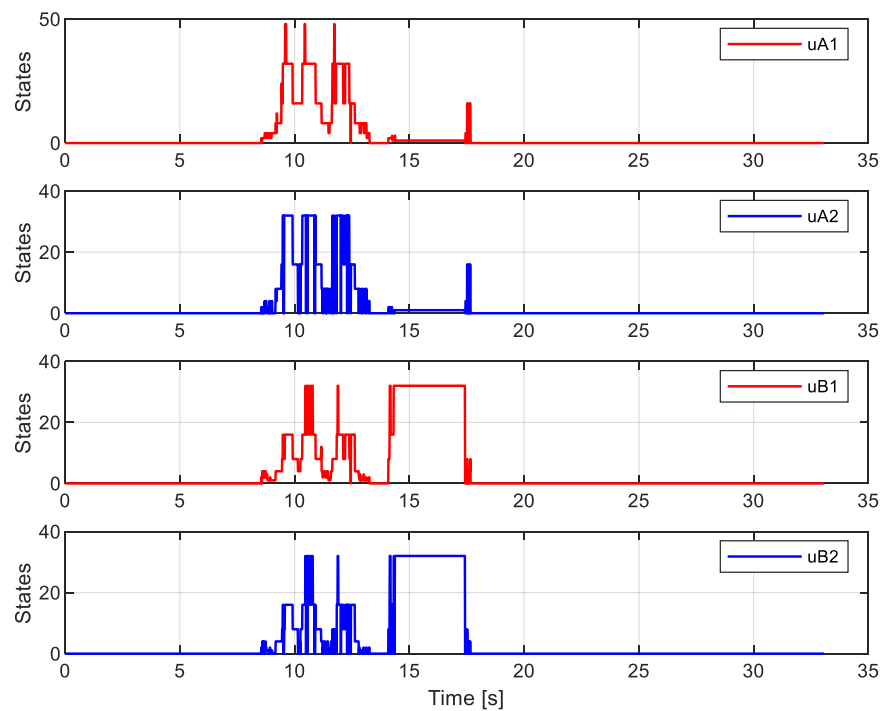


Figure 3.10. Switching of Valves with Selected Gain, Case Low Inertia

It is observed that when inertia of the boom is low, higher gain values than the selected gain values produces a slightly better switching behavior of the valves. With the lower gain, when boom is subjected to low inertia the switching of the valves during the first phase is slightly faster than with the low gain. During 2nd phase of motion the valves are

switching hyperactively so this behavior of valves switching makes it an inappropriate choice for the system. While in case of selected gain during the 2nd phase of motion, the valves change their states quite seldom. The switching behavior when inertia of the boom is low and gain values of the controller are lower than the selected gain values is shown in Figure 3.11

Since selected value of the gains produce a reasonable response of valves' switching when inertia of the boom is high and low. Hence these gain values are termed as default gain values for the controller for this study case.

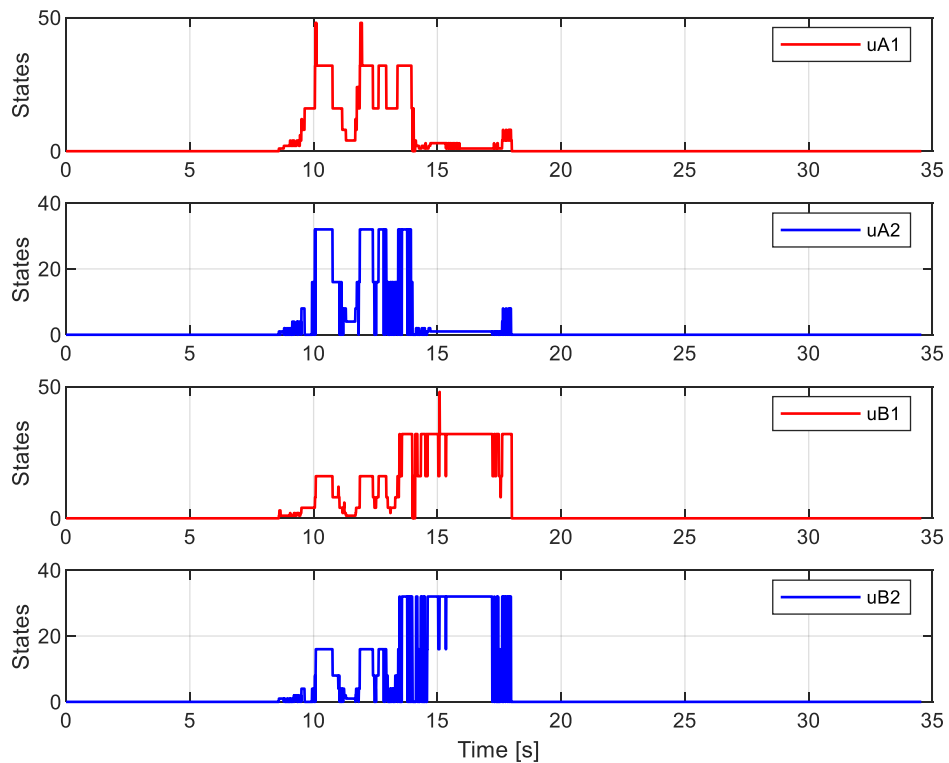


Figure 3.11. *Switching of Valves with Low Gain, Case Low Inertia*

Position trajectory when inertia of the boom is low with the selected gain is shown in Figure 3.12. Measured signal lags the reference signal but in this case during extension and retraction the difference between the measured and reference is less as compared to previous case when inertia of the boom is high.

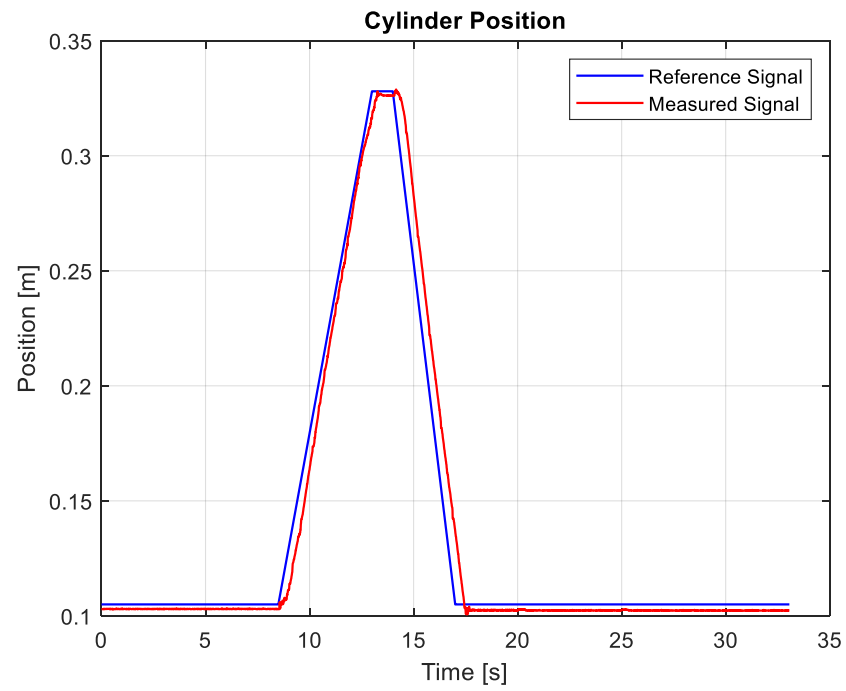


Figure 3.12. Position Trajectory, Case Low Inertia

The velocity profile of cylinder's motion with low boom's inertia is shown in Figure 3.13.

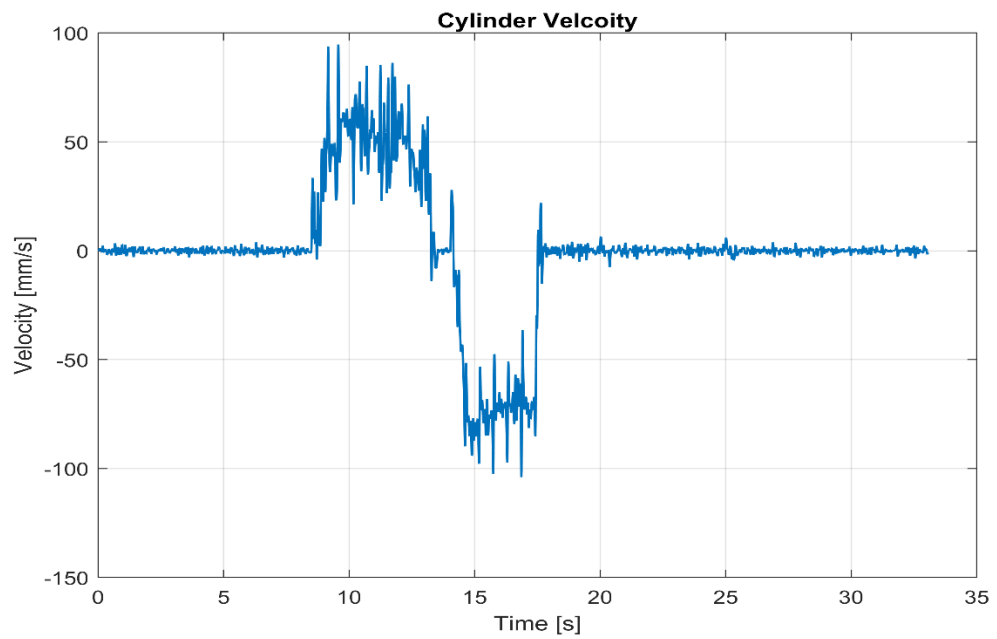


Figure 3.13. Filtered Velocity Profile, Case Low Inertia

4 MEASUREMENTS RESULTS

The purpose of these analysis is to determine the energy consumption and system's behavior when inertia of the boom is high. High inertia of the boom is obtained when boom is extended to maximum possible length. Due to limited space available in the laboratory boom cannot be extended fully.

4.1 High Inertia, Default Gain, Charged Accumulator

Multi-pressure system contains an accumulator as local pressure source for actuator. It means that hydraulic actuator is not directly coupled with the prime mover (in this case prime mover is an electric motor). Figure 4.1 explains the phases of operation and working principle of the multi-pressure system. When the cylinder starts to move at that instant pump is not providing flow to the system. Meanwhile, the pressure of the accumulator is decreasing. It shows that accumulator is providing the pressurized flow to the actuator. Pump turns on and starts to provide flow to the accumulator at 16 s. Cylinder is retracting at that instant. It shows that accumulator provides the pressurized flow to the cylinder during the extension phase solely. While retracting accumulator provides flow to the actuator during initial phase. Hence the purpose of integrated local energy source is fulfilled. An important thing to be mentioned here is that in all cases the movement of the cylinder starts in such a way that it first extends and then it retracts. Chamber A of cylinder is responsible for the extension of cylinder while chamber B is responsible for the retraction of cylinder.

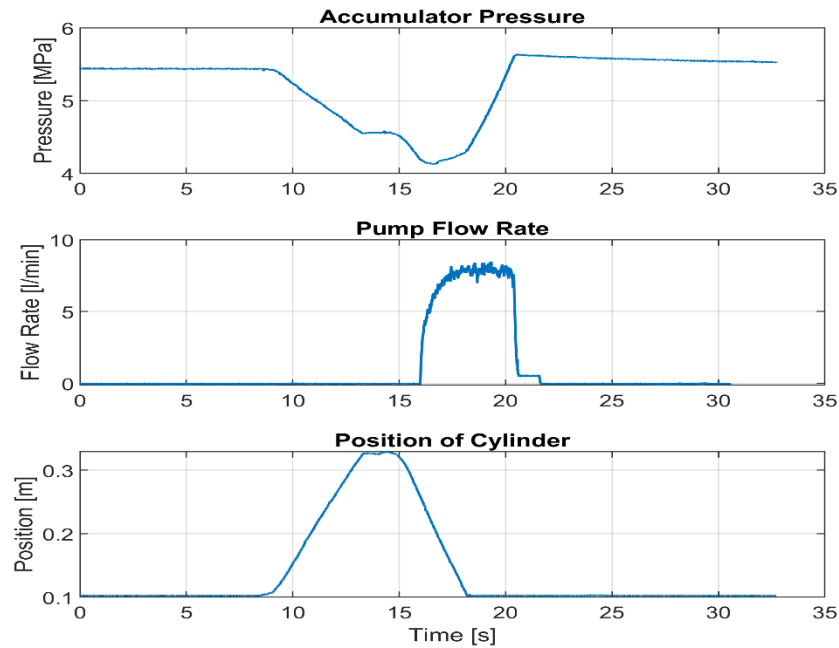


Figure 4.1. Working Principle of Multi-Pressure System, Scenario Charged Accumulator, Case High Inertia

Pump starts charging of the accumulator at 16 s. At that time cylinder is retracting and accumulator is providing flow to cylinder as well. Cylinder approaches the final position at 18.20 s and the motion of the cylinder becomes very slow. At that instant the pressure in the accumulator starts to increase rapidly. The flow rate provided by the pump reduces to zero at 20.64 s. Hence the pump provides flow to accumulator on for 4.64 s.

The analysis shows that multi-pressure system works as it is supposed to work. The accumulator provides the pressurized flow to the actuator and when the pressure in the accumulator reaches the minimum value, at that instant the pump starts to provide flow to the accumulator to charge it to the maximum value. These analyses show that pump does not require to meet the peak power requirements of the actuator because its only purpose is to charge the accumulator. Hence the dimensioning of accumulator is critical in this hybrid system. It is possible to size the pump according to the mean power requirement as it is not coupled with the actuator.

4.2 Energy and Power Consumption Analysis

The electrical input power is provided by batteries to the motor. Motor causes the pump to rotate and pump provides flow to the accumulator. The motor is controlled in such a way that it turns on only then when the pressure in the accumulator reaches the pre-charged value. The electric power is product of current and voltage. Electrical energy is obtained by the integration of electric power. The mechanical power is product of torque

and angular velocity and mechanical energy is determined by integration of mechanical power. Hydraulic power of the pump is the product of pump pressure and pump flow rate. Energy and power consumptions are shown in the Figure 4.2 and Figure 4.3 respectively.

It takes almost 10 s to perform a swing cycle. The pump supplies flow to accumulator for 4.64 s. Hence the input power is supplied for a very short duration of time. In the case of load sensing system, the input power from the diesel engine is taken for the whole cycle even when the actuator is not performing any operation. The Figure 4.2 shows the energy consumption during the swing operation.

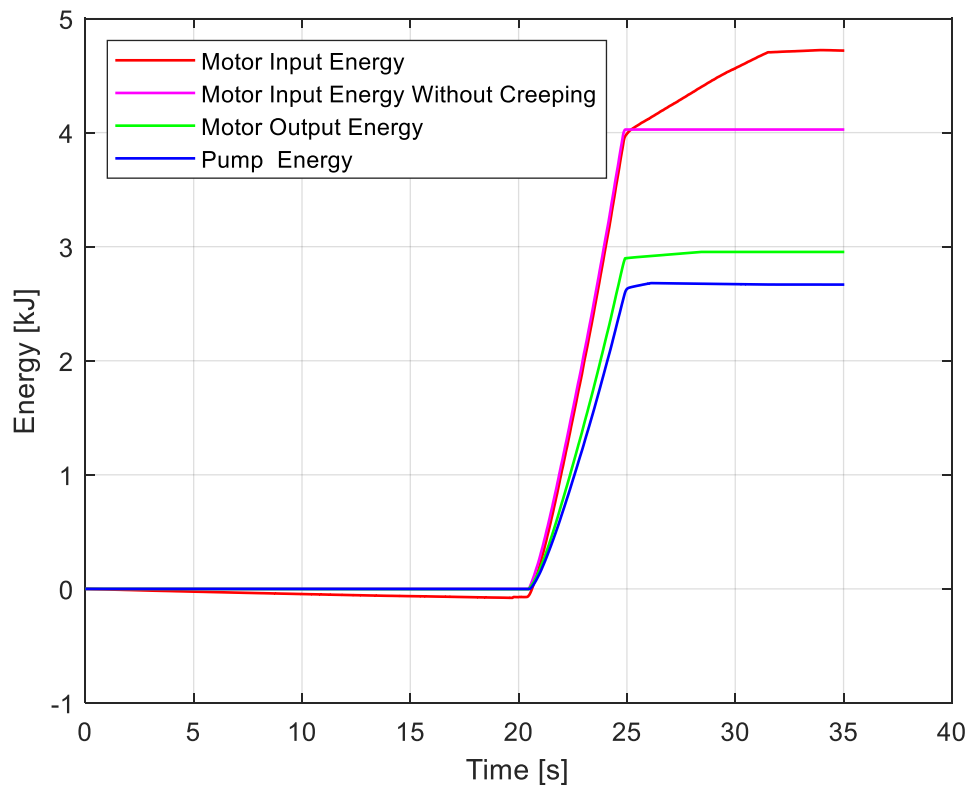


Figure 4.2. Energy Consumption, Scenario Charged Accumulator High Inertia

The electrical energy consumed during the complete cycle is 4.71 kJ. If the creeping of motor is ignored, then the electrical input energy consumption reduces to 4.02 kJ. This shows that creeping causes 0.69 kJ input energy losses. The mechanical energy consumption of the motor is 2.95 kJ and the hydraulic energy consumption is 2.66 kJ.

Electrical input power consumption, mechanical power consumption of motor and hydraulic power consumption by pump are shown in the Figure 4.3. Peak electrical input power when boom is subjected to high inertia is 1.26 kW, peak mechanical power of electric motor is 0.95 kW and peak hydraulic power of pump is 0.79 kW. These peak powers of the multi-pressure system are later compared with the peak powers of the modified load sensing system. The idea behind the comparison of peak powers is to

determine the possible downsizing of the electric motor and hydraulic pump with multi-pressure system.

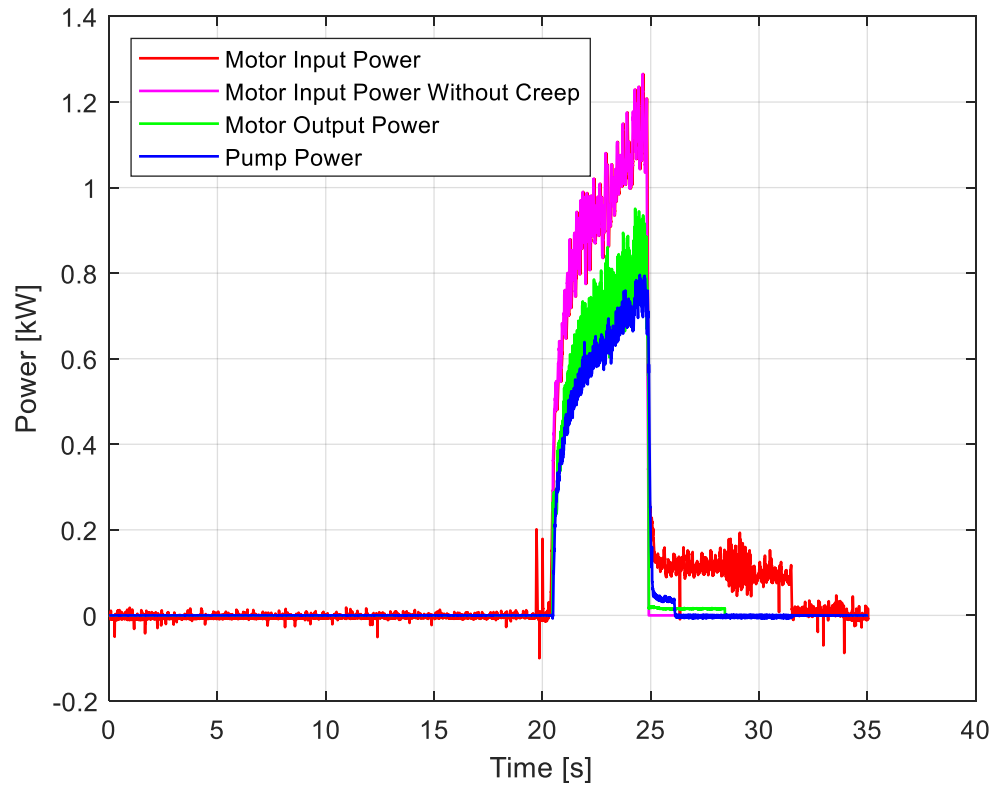


Figure 4.3. *Power Consumption, Scenario Charged Accumulator, Case High Inertia*

While performing tests it is observed that there are oscillations, when the cylinder approaches the final position. The analysis are performed to find out the possible reasons for the oscillation during cylinder's movement.

The analysis reveals that oscillations during cylinder motion occurs due to the pressure fluctuations in cylinder's chambers. It is observed that there are controllability issues when the velocity of the cylinder approaches the final position and velocity starts decreasing. The valves are switching frequently. So, there is a room for the improvement in the controller when cylinder approaches final position during extension. The detailed analysis of the system's behavior when inertia of the boom is high is showcased in the subsequent section 4.3.

4.3 Pressures in Cylinder Chambers

The pressure in cylinder's chambers, force and position trajectory of the cylinder are shown in the Figure 4.4.

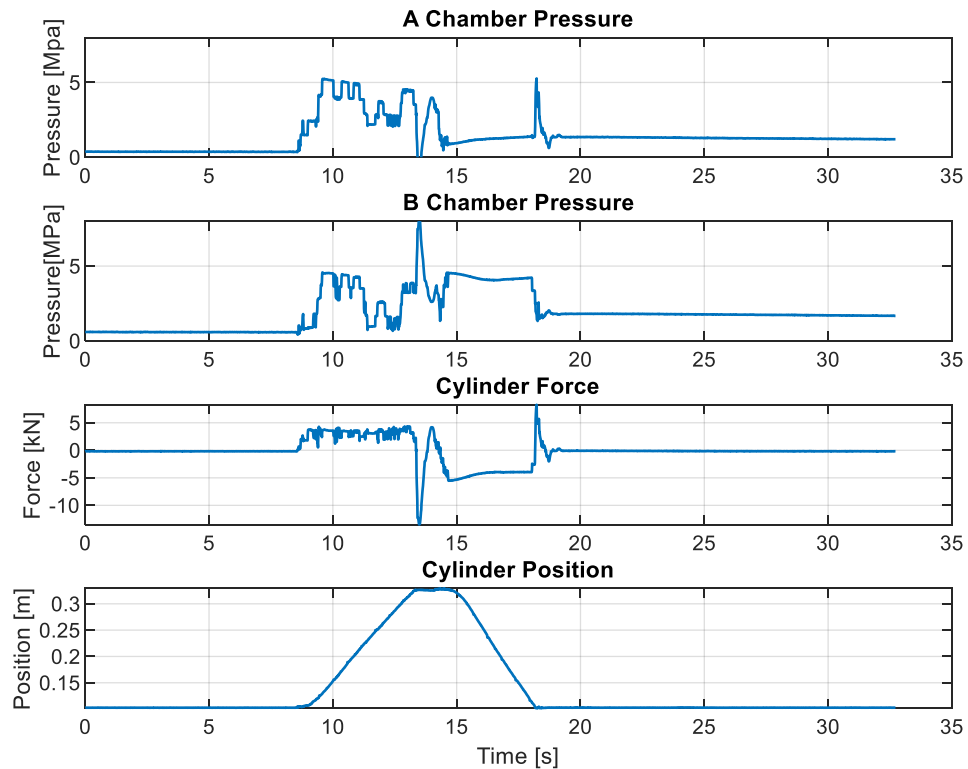


Figure 4.4. Cylinder's Chamber Pressure, Force and Motion Profile, Scenario Charged Accumulator, Case High Inertia

There are pressure fluctuations in both chambers of cylinders during movement. The analysis shows that these oscillations are more prominent when the cylinder is about to reach the final position during extension. During extension chamber A of the cylinder has high pressure while chamber B has lower pressure. This difference of the pressure is one of the reasons that allows the cylinder to extend. When the cylinder approaches the final position controller increases the cross flow due to which the pressure in B chamber starts to increase. This increase of pressure slows down the extension of the cylinder. When the pressure difference between both chambers is small there is still a position error of around 2 mm. When cylinder starts to retract it first achieves the reference position and then starts to retract. This causes oscillations in the cylinder motion at beginning of retraction phase of motion as shown in the Figure 4.5.

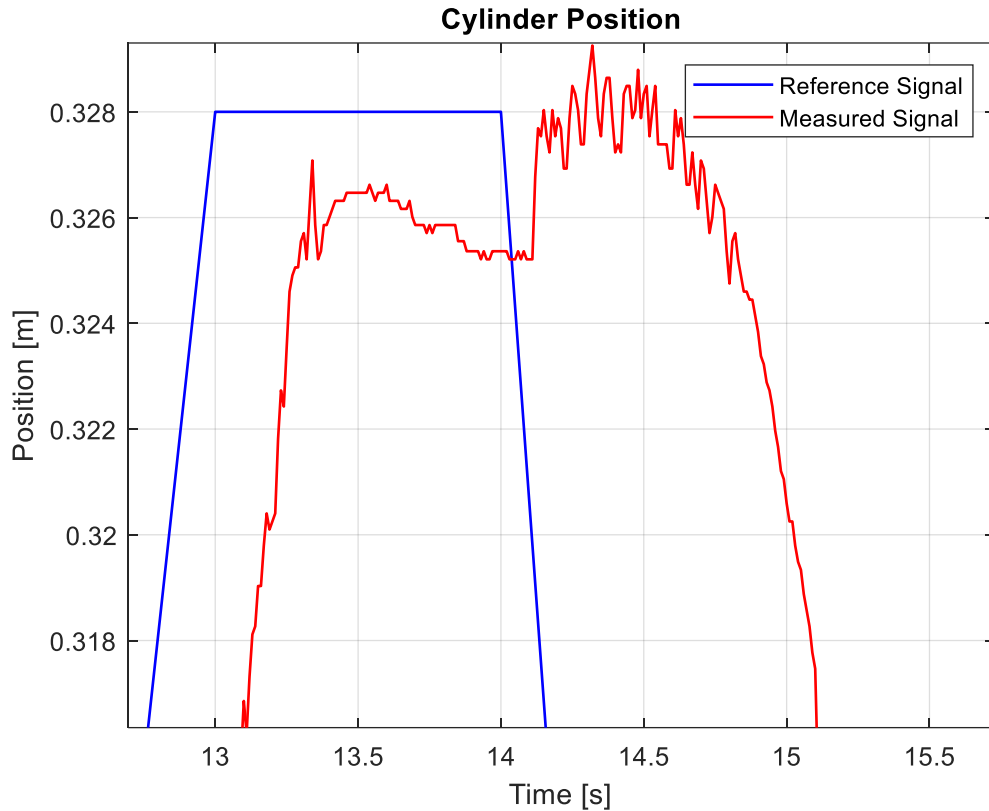


Figure 4.5. Reference Position & Measured Position Signal

During retraction of the cylinder, pressure in B chamber is higher than the chamber's A pressure. When cylinder is approaching the final position during retraction, the increase in the chamber A pressure slows down the retraction of cylinder. Pressure fluctuations are reasonable during the retraction as compared to extension phase of cylinder's motion. The net force of the cylinder is shown in Figure 4.6. When cylinder approaches to the final position force in B chamber of cylinder increases rapidly. Rapid increase of B chamber's force restrict the extension of cylinder motion. It is observed that during the extension phase of cylinder motion there are oscillations in the cylinder's force while during the retraction phase of cylinder motion the oscillations in the cylinder force are quite seldom. The oscillations in the cylinder's force during retraction occurs in the beginning when the cylinder is trying to approach the reference position signals as shown in the Figure 4.5.

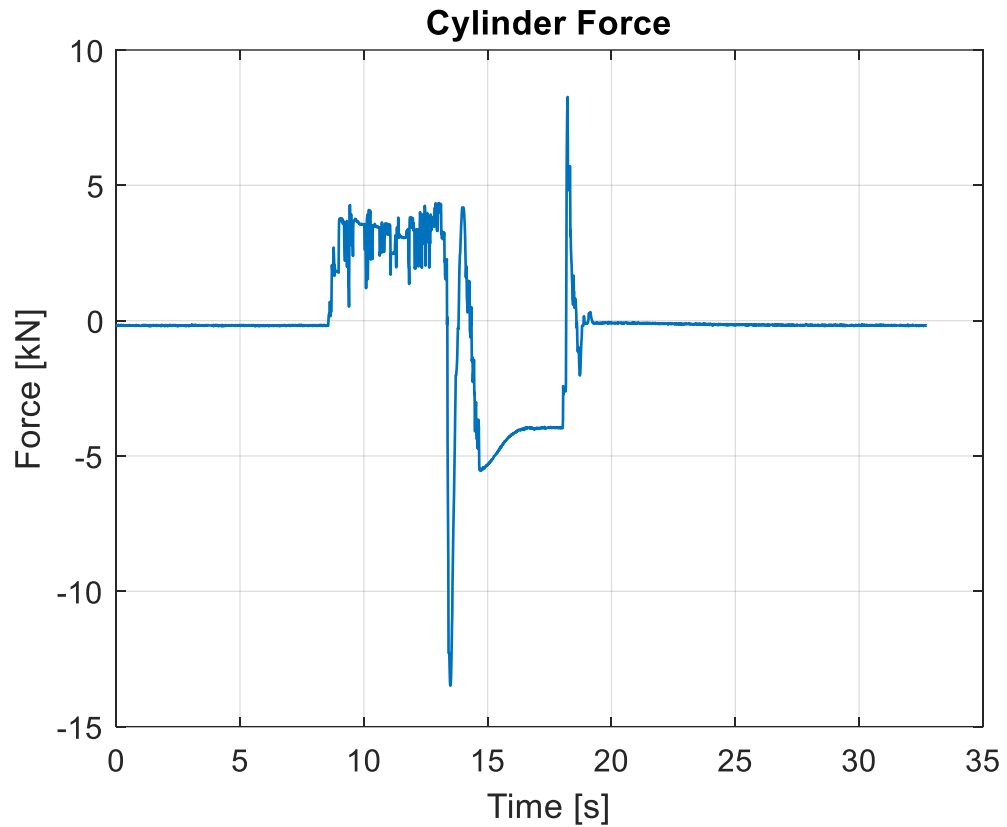


Figure 4.6. *Cylinder Force, Scenario Charged Accumulator, Case High Inertia*

These pressure fluctuations make the movement of the cylinder oscillatory. These fluctuations also induce noise and reliability concerns. As the flow coming into the actuator is being controlled by the valves so it is important to notice the behavior of the valves. Switching of the valves should be moderate, continuous switching of the valves reduces the life span of the valve and produces noise when the system is in operation. The detailed analysis of pressure fluctuations in cylinder's chambers and switching of the valves is analyzed to determine the cause of pressure fluctuations in cylinder's chambers.

The pressure fluctuations in cylinder chambers during the motion of the cylinder are showcased in Figure 4.7.

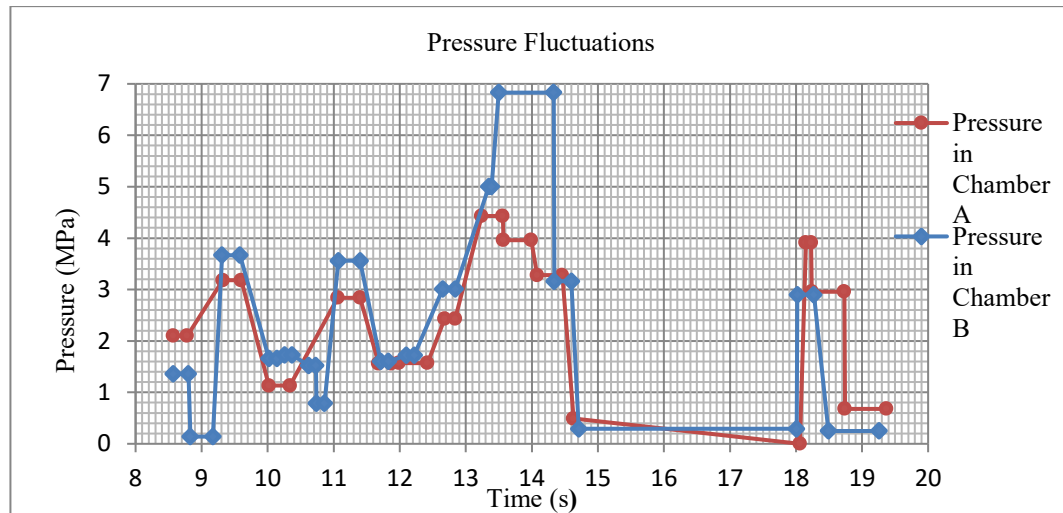


Figure 4.7. Pressure Fluctuations in Cylinder Chambers, Scenario Charged Accumulator, Case High Inertia

The pressure fluctuation analysis of chamber A and chamber B shows that pressure fluctuations are huge when cylinder is approaching the reference position during extension. The pressure fluctuation analysis are performed by comparing the high and low pressure during small time instants. Controller pushes the system to minimize the position error. The pressurized flow into the actuator is coming through the valves. It is important to observe that if the valves are switching frequently it shows that valves are hyperactive. The switching behavior of the valves connected with chamber A and chamber B of cylinder is shown in the Figure 4.8 and Figure 4.9 respectively.

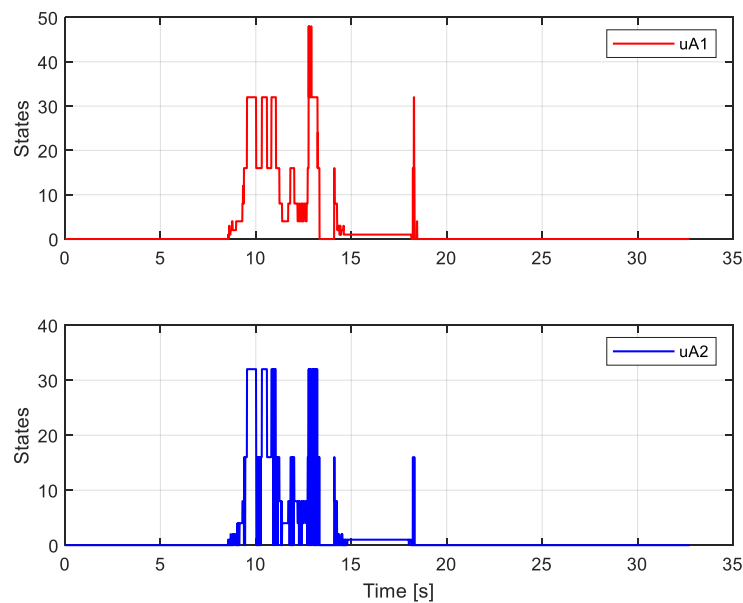


Figure 4.8. Switching behavior of Valves Connected to A Chamber, Scenario Charged Accumulator, Case High Inertia

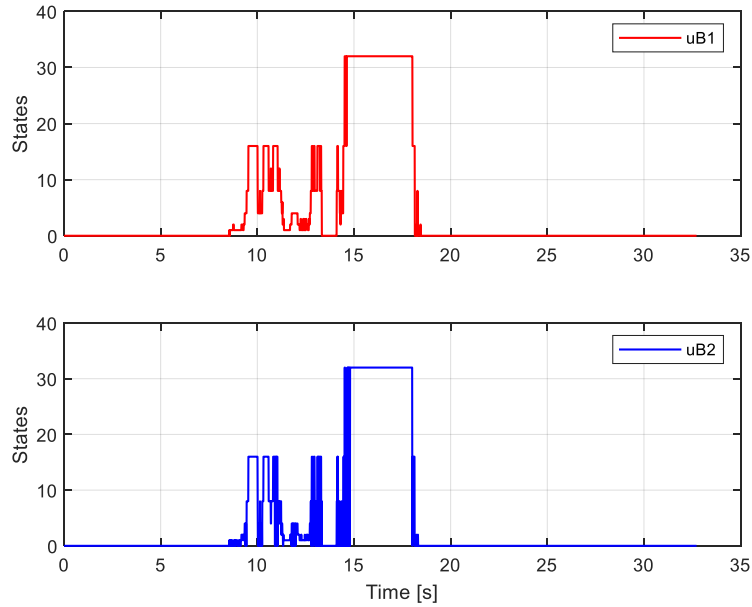


Figure 4.9. *Switching behavior of Valves Connected to B Chamber, Scenario Charged Accumulator, Case High Inertia*

The switching behavior of the valves shown in Figure 4.8 and Figure 4.9 indicates that both parallel valves are opened. The both parallel valves are opened to provide the maximum flow rate to actuator. The valves are hyperactive which means that they are switching continuously. This continuous switching of the valves produces pressure fluctuations in cylinder chambers. The pressure fluctuations ultimately induce oscillations in the cylinder motion. It is observed that switching becomes frequent when cylinder is approaching the reference position during extension. While retraction the state of change is far better than during extension. The frequent switching of the valves and huge pressure fluctuations raise concerns about the noise and durability of the hydraulic components.

4.4 Low Inertia

Low inertia of the boom is obtained by retracting the boom to minimum possible length. The purpose of these analysis is to determine the energy consumption and system behavior when the inertia of the boom is low. The working principle of the system is shown in Figure 4.10.

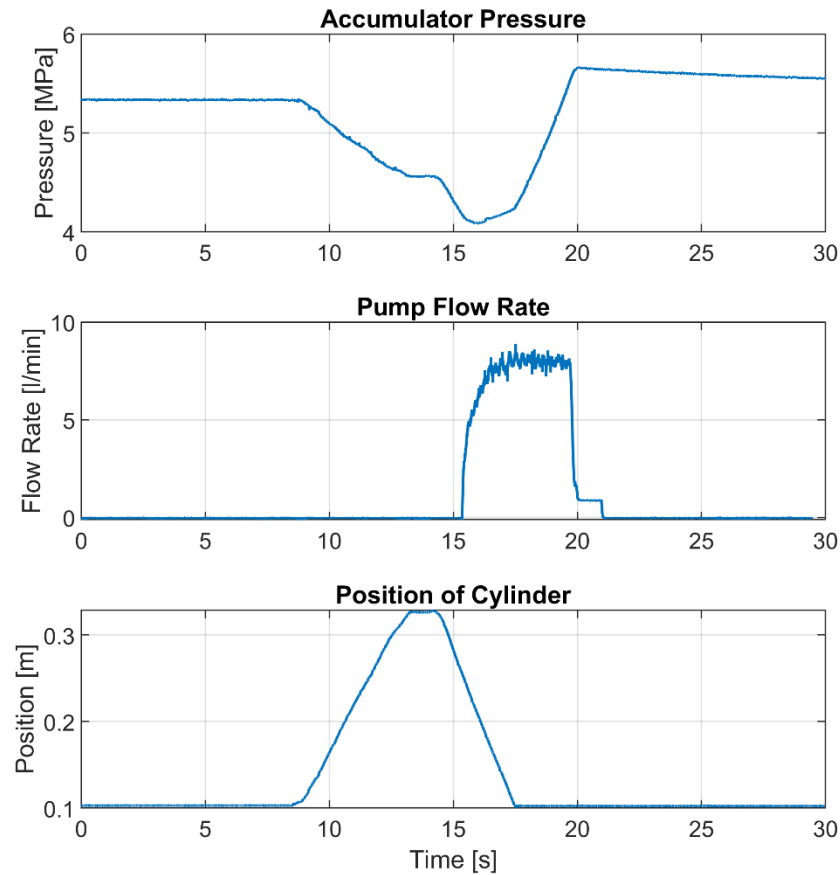


Figure 4.10. Working Principle of Multi-Pressure System, Scenario Charged Accumulator, Case Low Inertia

When accumulator is charged it provides flow to the actuator during the extension phase of motion. When the pressure in the accumulator drops below the pre-charged pressure value then the pump starts to provide pressurized fluid to the accumulator. The pump starts to provide flow at 15.36 s in this case, while in previous case it starts to provide flow at 16.0 s. At 15.36 s cylinder is already retracting. Hence, in this case also accumulator solely provides the flow to the system during the whole extension phase of cylinder movement. Pump stops to rotate at 20.02 s. Hence it remains on for 4.66 s. For the actuator it takes almost 9.18 s to complete the swing operation when boom's inertia is low. In case of high inertia boom takes 10 s to perform one swing cycle. Pump provides the flow to the actuator until accumulator pressure reaches the maximum pressure value. During the retraction phase when pump starts to provide flow to the accumulator and the accumulator is also providing flow to the actuator, so the pressure increases slowly in the accumulator. When cylinder approached the final position and it has lower velocity then pressure in the accumulator increases rapidly.

4.5 Power and Energy Consumption Analysis

The energy consumptions are shown in the Figure 4.11.

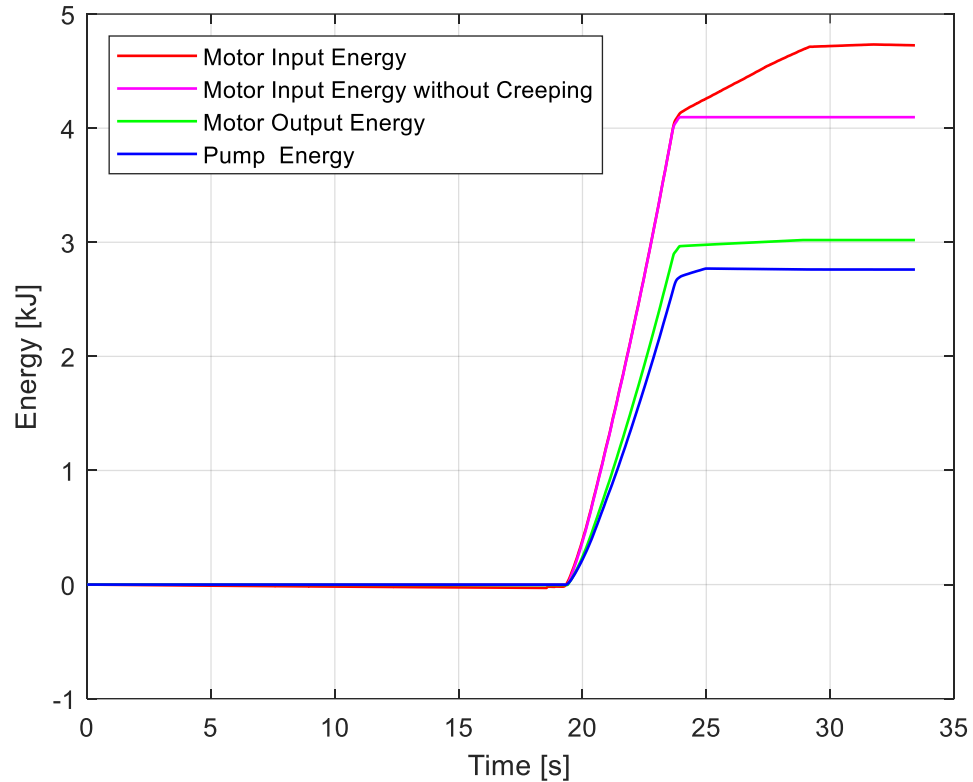


Figure 4.11. Energy Consumption, Scenario Charged Accumulator, Case Low Inertia

The energy consumption analysis reveals that when the inertia of the boom is low, the electrical input energy is 4.72 kJ. If the creeping of the electric motor is ignored than the electrical input energy consumption is 4.09 kJ. In case of high inertia, the energy consumption is 4.02 kJ. The analysis shows that there is only a slight difference between the electrical input energy consumption when the boom is subjected to high and low inertia. The mechanical energy consumed by the electric motor is 3.01 kJ and hydraulic energy consumption is 2.76 kJ. In case of high inertia the hydraulic energy consumption is 2.66 kJ.

The energy consumption analysis indicates that when the boom is subjected to low inertia then the energy consumption is fractionally higher than when it is subjected to high inertia. The difference between the energy consumption is not huge and on a broad scope it can be concluded that energy consumption when boom is subjected to high and low inertia is almost the same.

The power consumption is shown in Figure 4.12. The peak electrical input power is 1.23 kW, peak hydraulic power is 0.80 kW and peak mechanical power of electric motor is 0.95 kW. The peak power consumptions when inertia of the boom is low are almost identical to the peak power consumptions when inertia of the boom is high. The peak power consumption analysis are performed to determine the possible reduction in the size of electric motor and hydraulic pump.

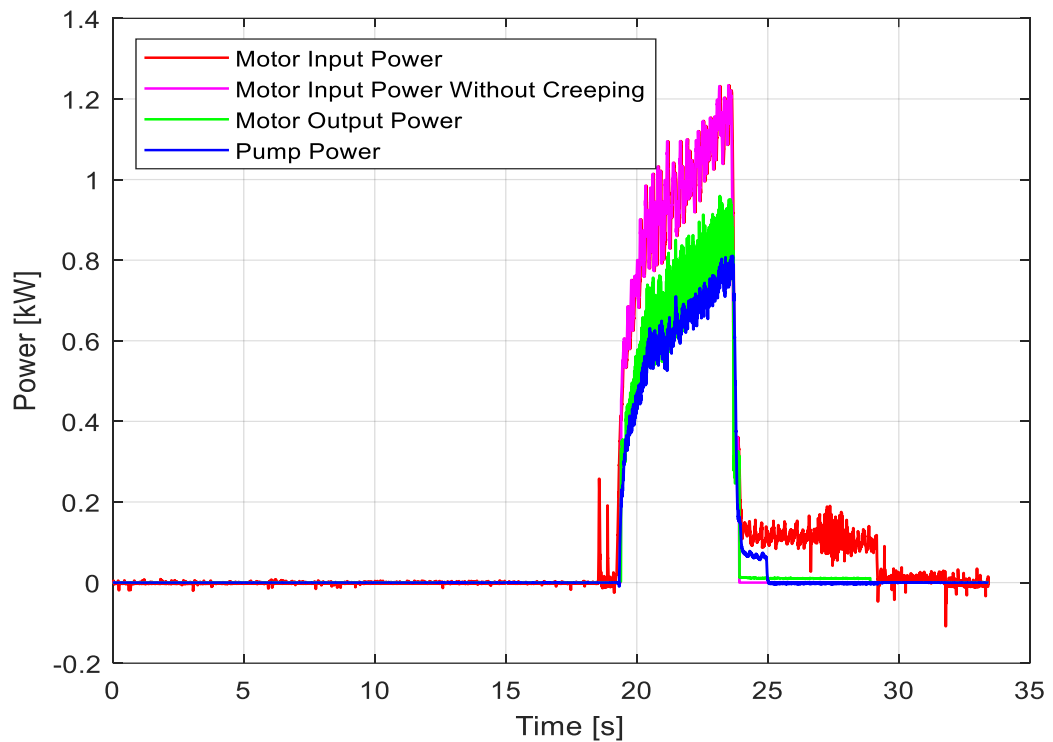


Figure 4.12. Power Consumption, Scenario Charged Accumulator, Case Low Inertia

4.6 Cylinder Chambers' Pressures

Cylinder chambers' pressures, resultant force and position profile is shown in Figure 4.13. There are fluctuation in the pressure during the extension phase of cylinder's motion. The force graph shows that there are oscillation in the cylinder's force during the extension phase and these oscillations are quite seldom during the retraction phase of cylinder's motion.

The behavior of the systems in terms of cylinder chambers pressure, cylinder force and cylinder motion is almost the same which was observed when the inertia of the boom is high. The only difference is in the magnitude of the force. When the inertia of the boom is low the force is relatively low as compared to when inertia of the boom is high.

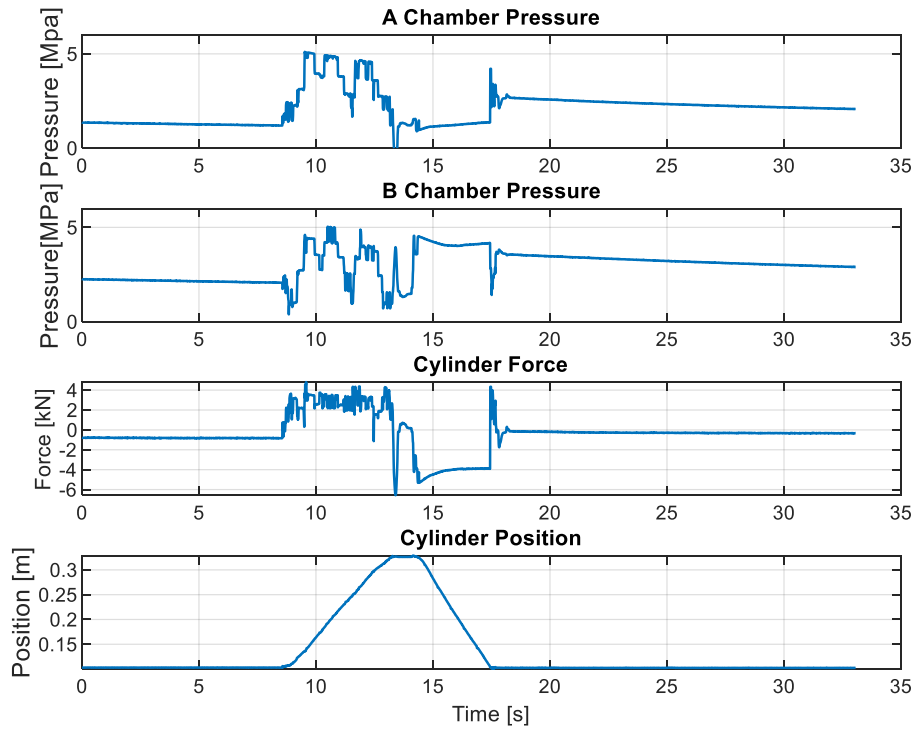


Figure 4.13. *Cylinder Chambers' Pressures, Scenario Charged Accumulator, Case Low Inertia*

Cylinder extends from 0.105 m to 0.328 m and retracts when it changes position from 0.328 m to 0.105 m. During the extension phase of pressure in cylinder A chamber is greater than the chamber's B pressure. Similarly during retraction phase the pressure in B chamber is greater than chamber's A pressure.

It is observed that there are oscillations in cylinder's motion during swing cycle. Figure 4.14 indicates that there are pressure fluctuations in chambers when it approaches the target position. Controller pushes the system to minimize the position error. During extension and retraction when the position control is turned on and cylinder starts its motion it first achieves the reference position and then it starts to move. This is one of the reasons for the measured position signals to lag the reference signal. The cylinder force is shown in Figure 4.15. The force plot shows that there are oscillations in the cylinder force during the extension phase of motion while during the retraction the oscillations in the force are seldom. The pressure oscillations causes oscillation in the cylinder force and motion.

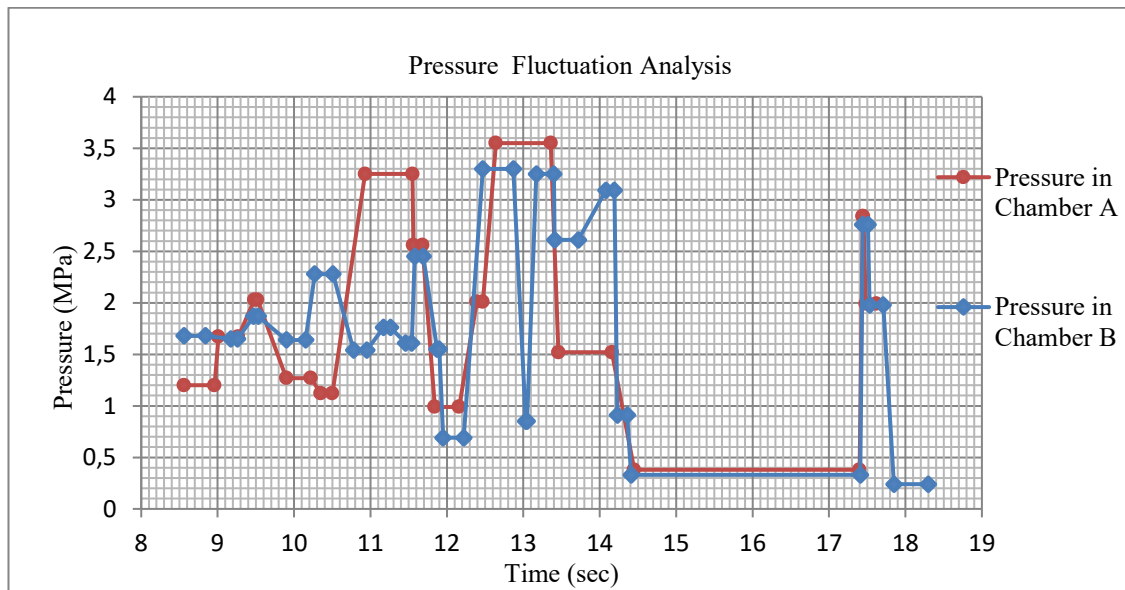


Figure 4.14. Pressure Fluctuations in Cylinder Chambers, Scenario Charged Accumulator, Case Low Inertia

The cylinder's force is shown in Figure 4.15.

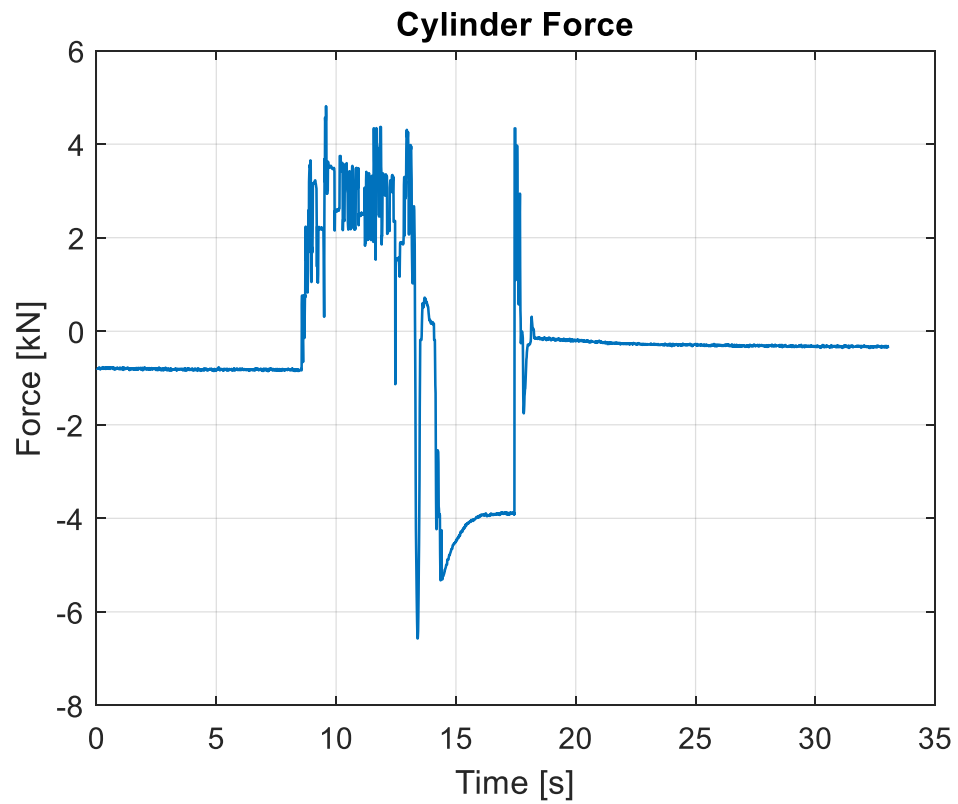


Figure 4.15. Cylinder Force, Scenario Charged Accumulator, Case Low Inertia

The switching behavior of the valves is shown in Figure 4.16 and Figure 4.17. The switching behavior of the valves show that during the extension phase of cylinder's motion the valves are switching hyperactively while during the retraction phase of cylinder's motion the valves' switching is seldom.

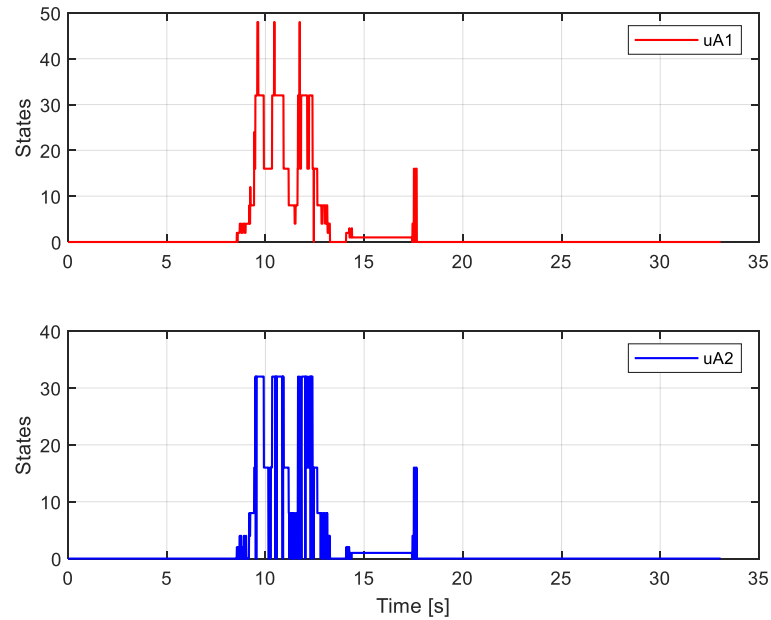


Figure 4.16. Valves Connected to A Chamber, Scenario Charged Accumulator, Case Low Inertia

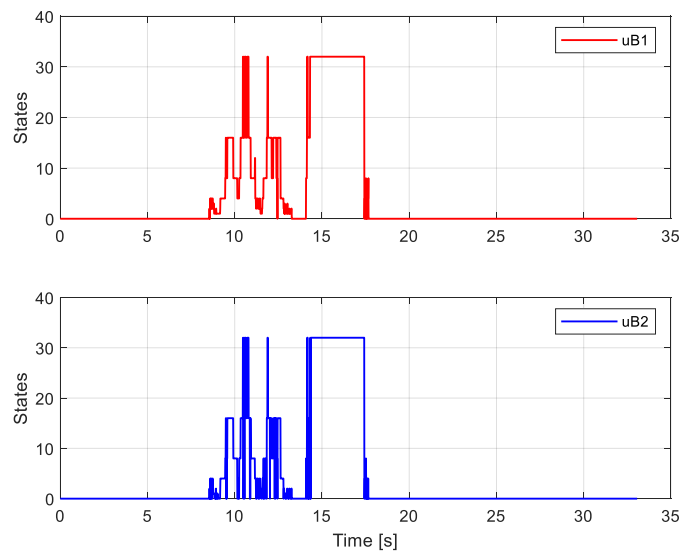


Figure 4.17. Valves Connected to B Chamber, Scenario Charged Accumulator, Case Low Inertia

4.7 Empty Accumulator Analysis

In multi-pressure hydraulic system accumulator is integrated with actuator as a local pressure source. It is observed during the previous tests that accumulator used in this system can solely provide the flow actuator during the extension phase. To determine the effect of pressure variation in the accumulator on energy consumption, these tests are performed with the minimum pressure in the accumulator. In these tests the initial pressure in the high pressure accumulator circuit is around 1 MPa.

The purpose of these analysis is to determine the energy and peak power consumption when the accumulator is empty which means that all the hydraulic fluid is released from the high pressure accumulator.

4.8 High Inertia

The working principle of the system is shown in the Figure 4.18.

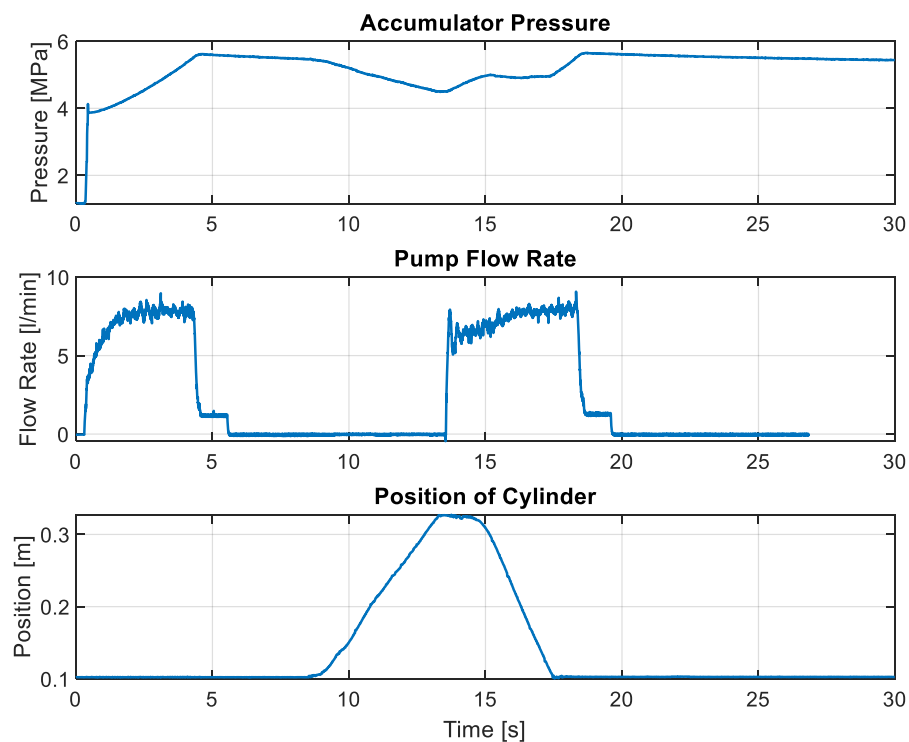


Figure 4.18. Working Principle of Multi-Pressure System, Scenario Empty Accumulator, Case High Inertia

The tests performed with the empty accumulator show that as soon as the system starts, the controller command the motor to turn on to charge the accumulator. Once the accumulator is charged to maximum pressure value, the pump flow reduces to zero.

Cylinder starts to move at 8.57 s. At that time pump remains off and at that instant the accumulator starts to discharge and for the initial movement of the cylinder the flow rate is provided by the accumulator. The accumulator reaches the pre-charged pressure value at 14.93 s and at that instant pump provides the flow to the accumulator to charge it again. The working principle of the multi-pressure system is validated through these analyses.

4.9 Power and Energy Consumption Analysis

The energy consumption analysis is presented in Figure 4.19.

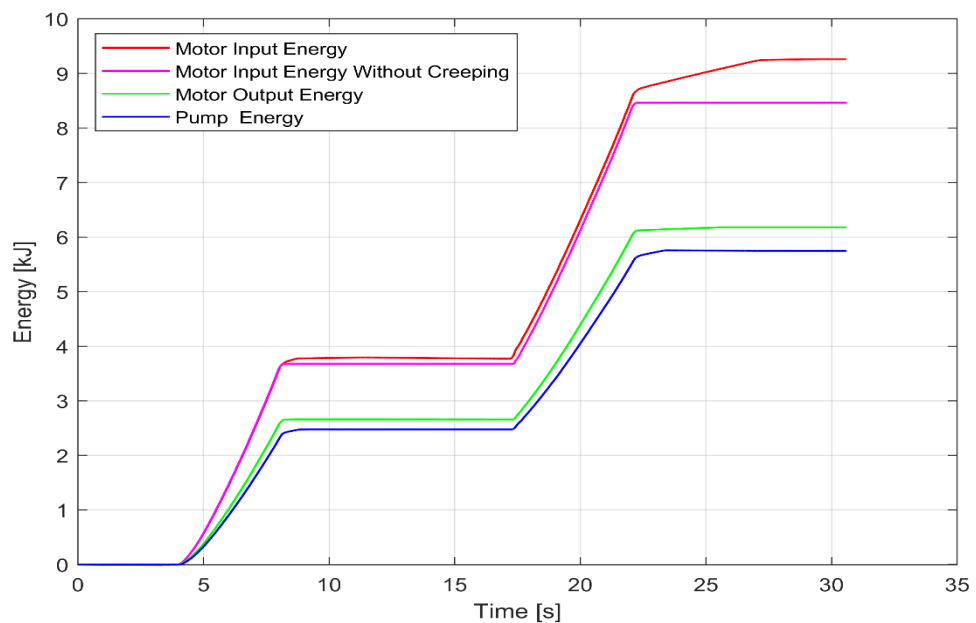


Figure 4.19. Energy Consumption, Scenario Empty Accumulator, Case High Inertia

Analysis shows that electrical input energy consumed in this case is 9.21 kJ. If the creeping of electric motor is ignored, then the electric energy consumed is 8.46 kJ. This energy consumed in this case is almost double when the operation is performed with charged accumulator because motor turns on twice and charges the accumulator twice in this case. The power consumptions are shown in Figure 4.20.

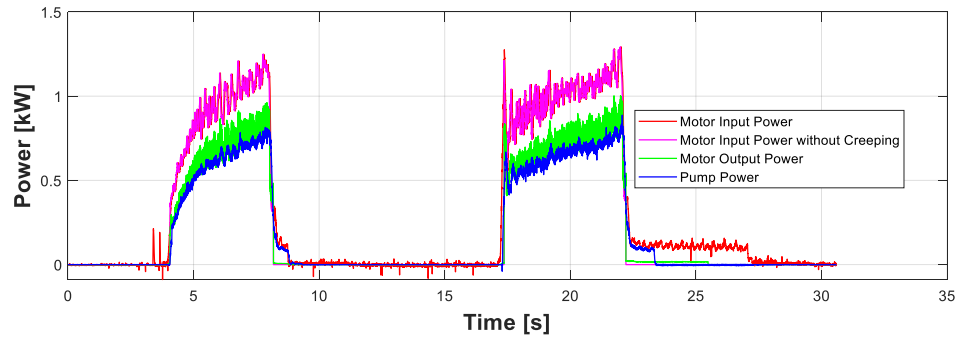


Figure 4.20. Power Consumption, Scenario Empty Accumulator, Case High Inertia

4.10 Low Inertia

These analyses are carried out to determine the energy and power consumption when the boom is subjected to low inertia and the accumulator is empty. The working principle of the system is shown in Figure 4.21.

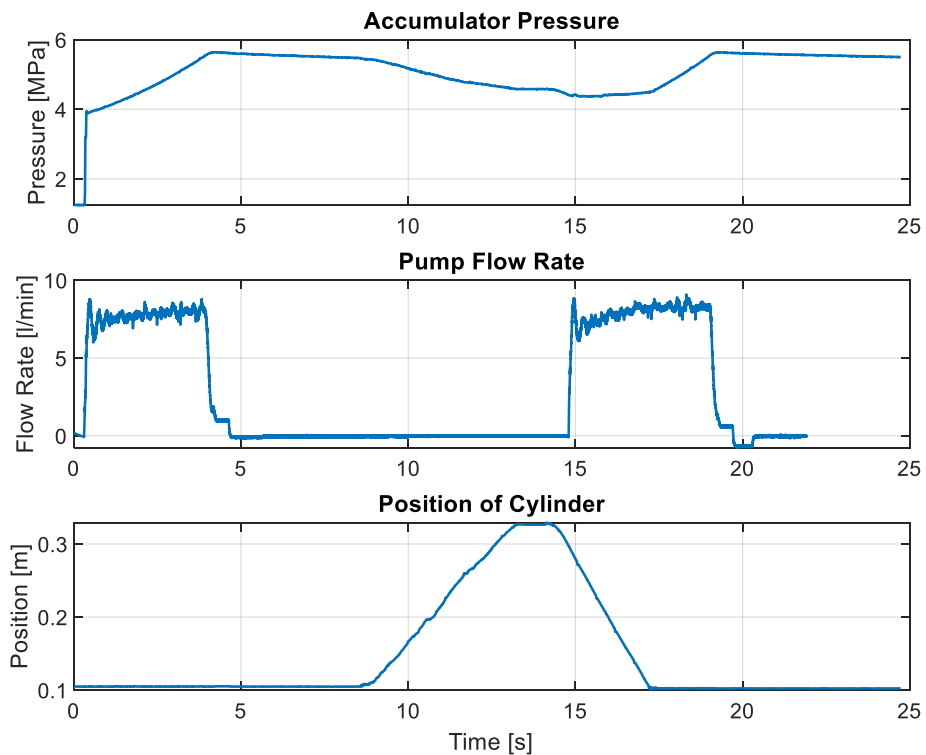


Figure 4.21. Working Principle of Multi-Pressure System, Scenario Empty Accumulator, Case Low Inertia

Cylinder starts to move at 8.60 s. At that time pump remains off and at that instant the accumulator starts to discharge and for the initial movement of the cylinder the flow rate

is provided by the accumulator. The accumulator reaches the pre-charged pressure value at 14.70 s and at that instant pump provides the flow to the accumulator to charge it again. The working principle of the multi-pressure system is validated through these analyses when inertia of the boom is low.

4.11 Power and Energy Consumption Analysis

Energy consumptions when the accumulator is empty and inertia of the boom is low are shown in the Figure 4.22.

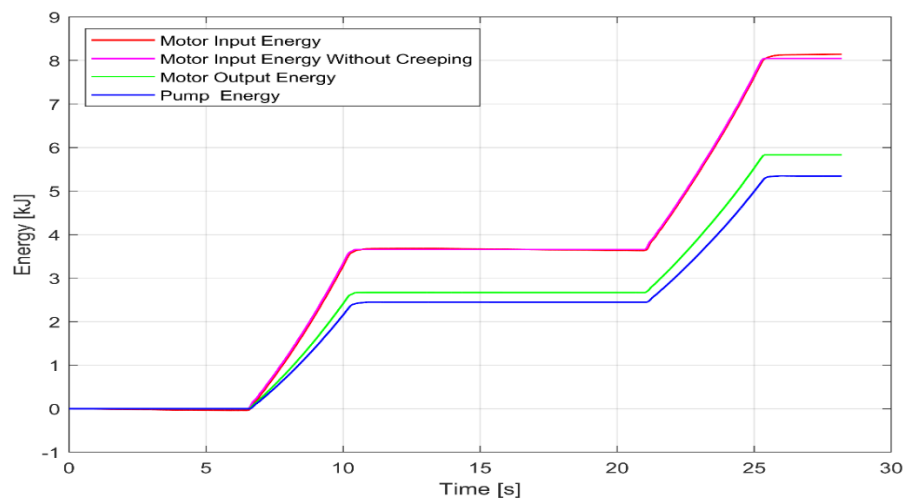


Figure 4.22. Energy Consumptions, Scenario Empty Accumulator, Case Low Inertia

Electrical input energy consumption without creeping of electrical motor is 8.04 kJ. In the case of charged accumulator, the electrical input energy consumption is 4.09 kJ. The electrical input energy consumption is close to double because the motor turns on twice to charge the accumulator in this case. Motor's mechanical energy consumption is 5.83 kJ. Hydraulic energy consumption by pump is 5.34 kJ. The power consumption is shown in Figure 4.23. Peak electrical input power is slightly higher than the charged accumulator case and reaches to 1.41 kW while in case of charged accumulator it is 1.26 kW.

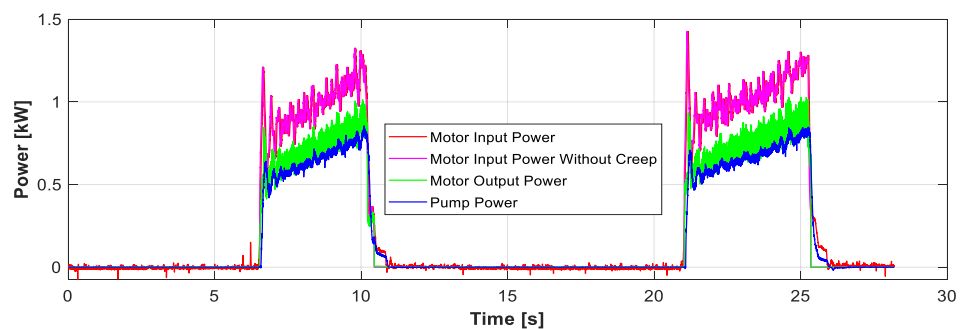


Figure 4.23. Power Consumption, Scenario Empty Accumulator, Case Low Inertia

5 EFFICIENCY ANALYSIS

The preliminary focus of research is to compare the energy consumption of multi-pressure system with the modified load sensing system. The energy consumption analysis is performed to determine electrical input energy consumption, motor's mechanical energy consumption and hydraulic energy consumption. The detailed analysis is presented in this chapter along with the percentage reduction in the energy consumption.

5.1 Energy Efficiency Analysis, High Inertia

In order to analyze the energy efficiency of system peak power and energy input parameters were evaluated and boom is subjected to high inertia.

Table 5.1. *Energy and Peak Power Consumption Analysis, Boom's High Inertia*

Parameter along with units	Modified load sensing system	Multi pressure system
Electric Energy Consumption (kJ)	15.43	4.01
Motor mechanical Energy Consumption (kJ)	13.33	2.95
Hydraulic Energy Consumption (kJ)	10.84	2.66
Peak electric Input power (kW)	4.30	1.26
Peak mechanical power of Electric motor (kW)	3.10	0.95
Peak hydraulic power of pump (kW)	2.47	0.79

Table 5.1 indicates that energy consumption in the modified load sensing system is much larger than in the case of multi-pressure system. In the case of modified load sensing system the electrical energy consumption is 15.43 kJ and with the implementation of the multi pressure system the electrical input energy reduces to 4.01 kJ if creeping of the motor is ignored. So overall the electrical input energy consumption reduces up to 74%.

The motor's mechanical energy consumption with modified load sensing system is 13.33 kJ meanwhile in the case of multi pressure system that the energy consumption reduces up to 77.86% which is only 2.95 kJ.

Similar observations were made for the hydraulic energy consumption. The energy consumption for multi-pressure system reduces 75.46% when compared with load sensing system.

The trend for power consumption for multi pressure system was observed to be similar to the energy usage. Overall the electric and hydraulic peak powers with MPS are considerably less than that of modified load sensing system. Peak power calculations give

an idea about possible downsizing of prime mover and hydraulic pump as compared to conventional modified load sensing system. Peak power analysis suggests that size of electric motor and hydraulic pump can be reduced up to 1/3 as compared to modified load sensing system. Comparative energy and peak power consumptions are shown in Figure 5.1.

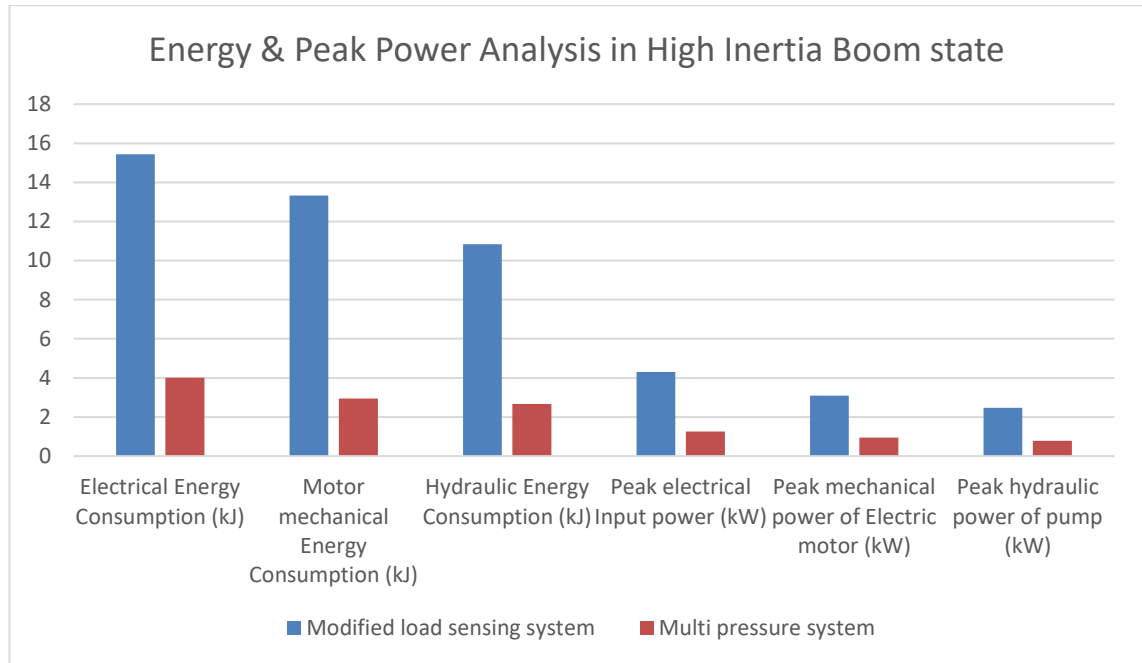


Figure 5.1. Energy & Peak Power Analysis, Boom in High Inertia state

We can derive from afore results demonstrated in Figure 5.1 that on average up to 70% less energy is required if multi pressure system is executed when boom is in state of high inertia.

5.2 Energy Efficiency Analysis, Low Inertia

Table 5.2 shows the energy and peak power consumptions of MPS and MLS.

Table 5.2. Energy and Peak Power Consumption Analysis, Boom's Low Inertia

Parameter along with units	Modified load sensing system	Multi pressure system
Electric Energy Consumption (kJ)	14.92	4.09
Motor mechanical Energy Consumption (kJ)	12.91	3.01
Hydraulic Energy Consumption (kJ)	10.14	2.66
Peak electrical Input power (kW)	2.93	1.23
Peak mechanical power of Electric motor (kW)	2.03	0.95
Peak hydraulic power of pump (kW)	1.85	0.80

With modified load sensing system when the boom is subjected to low inertia then electrical input energy consumption is 14.92 kJ. Whereas in case of multi-pressure system, the electrical energy consumption is 4.09 kJ if creeping is ignored. Overall electrical energy consumption reduces to 72%.

The mechanical energy consumption of electric motor is 12.91 kJ with modified load sensing system. In case of multi-pressure system, the mechanical energy consumed by electric motor is 3.01 kJ. Mechanical energy consumption reduces to 76%.

In the same way hydraulic energy consumption is 10.14 kJ with modified load sensing system. In case of multi-pressure system, the hydraulic energy consumption is 2.66 kJ the hydraulic energy consumption reduces to 73%.

The peak electrical input power for MLS system is 2.93kW and for Multi pressure system is 1.23 kW which is almost half of the system. As well as mechanical power of Electric motor for multi pressure system is 53% less than modified sensing system. And the peak hydraulic power of pump for modified load sensing system is 1.85kW and for multi-pressure system is 0.80kW. Peak power analysis suggests that size of electric motor and hydraulic pump can be reduced more than half; as compared to modified load sensing system. Comparative energy and peak power consumptions are shown in Figure 5.2

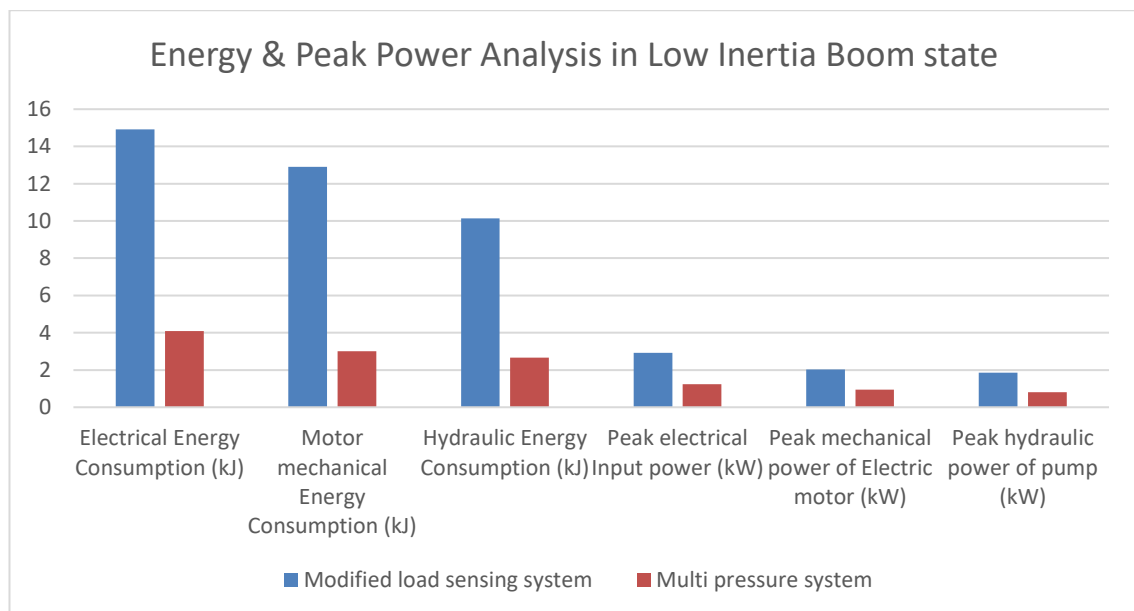


Figure 5.2. Energy & Peak Power Analysis, Boom in Low Inertia state

The graph demonstrated in Figure 5.2 that on average less than 70% energy is required if multi-pressure system is executed and boom is in state of high inertia. Also peak electrical input power reduces up to 50%.

6 DISCUSSIONS

The experimental results have demonstrated that multi-pressure system have the potential to reduce the energy input energy consumption. The results also showcased that it is possible to downsize the prime mover and implement decoupling between prime mover and actuator.

Although the input energy reduces up to 70% but still in this research work the energy consumption and power losses in the valves and hoses are not known. Therefore, it is recommended to measure these losses and to investigate the possibilities to reduce their amount in practice. Determination of these power losses will help to improve the energy efficiency.

Furthermore, it would be interesting to implement the multi-pressure system to perform the lift and tilt operations of boom. It would be informative to investigate the operating capability and energy efficiency of this system when multiple actuators are working together. Since, this system is designed to replace one conventional proportional valve hence to perform all the operation four packages of multi-pressure systems are required to cover all boom operations. The allocation of multi-pressure system on the excavator is another challenge. Due to limitations in the measurement equipment factors such as friction of bearing, cylinder friction and power losses of the inverter and pump are not considered in this thesis. It would be good to categorically analyze these power losses which will help to enhance the energy efficiency.

Finally, it would increase the understanding of the potential of hydraulic hybridization if the energy consumption with this system would be compared with the energy consumption of the promising techniques which have been mentioned in chapter 2.5.

7 CONCLUSIONS

In current research work multi-pressure hydraulic system is implemented on a mini excavator to perform the swing operation. The core purpose of research work was to implement the multi-pressure system on a mini excavator and then evaluate the energy/power consumption when the inertia of the boom is high and low consequently. Finally, the energy and power consumptions of MPS are compared with the modified load sensing system's energy and power consumption.

Results reveal that energy consumption can be reduced up to 71% by implementing multi-pressure system as compared to modified load sensing system. The research in this thesis work shows that there are only slight variations in the energy consumption when the boom is subjected to high and low inertia. Electric and hydraulic peak powers are relatively smaller than in the modified load sensing system. In the case of conventional modified load sensing system, the pump flow rate was set at 18 l/min whereas in research work the pump flow rate is maintained around 8 l/min to perform the swing operation. The results demonstrate that system is capable to perform the operation efficiently with the reduced pump flow rate and the pump size can be reduced to half.

In current study the prime mover is an electric motor and maximum peak power observed with multi-pressure system is 1.4 kW. While in case of MLS maximum peak electrical input power is 4.30 kW. Hence, with the multi-pressure system the size of electric motor can be reduced up to 1/3 compared with the size of electric motor used in modified load sensing system.

The pressure fluctuations in the cylinder chambers are observed during the extension phase of cylinder motion. These pressure fluctuations induce noise, durability and controllability concerns in the system. The key feature of this system is that these pressure fluctuations are dealt locally with the help of accumulator and pressure transformers. This feature ensures that the actuator is not directly coupled with the prime mover. In case of conventional load sensing system pressure and power fluctuations in the actuator induces fluctuations in the prime mover.

The overall system efficiency improved by modifying the afore-mentioned parameters and implementing multi pressure system. The goals of energy efficiency, decoupling of actuator and prime mover as well as downsizing of prime mover and hydraulic pump are achieved successfully.

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